DOE Science Initiative

Advanced Modular Inverter Technology Development

Final Report

Reporting Period Start: March 2004
Reporting Period End: November 2005

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Report Date: 20 January 2006

DOE Award DE-FC26-04NT41972

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Abstract

Introduction – Inverter technology

Electric and hybrid-electric vehicle systems require an inverter to convert the direct current (DC) output of the energy generation/storage system (engine, fuel cells, or batteries) to the alternating current (AC) that vehicle propulsion motors use. Vehicle support systems, such as lights and air conditioning, also use the inverter AC output. Distributed energy systems require an inverter to provide the high quality AC output that energy system customers demand. Today's inverters are expensive due to the cost of the power electronics components, and system designers must also tailor the inverter for individual applications. Thus, the benefits of mass production are not available, resulting in high initial procurement costs as well as high inverter maintenance and repair costs.

Electricore, Inc. (www.electricore.org) a public good 501 (c) (3) not-for-profit advanced technology development consortium assembled a highly qualified team consisting of AeroVironment Inc. (www.aerovironment.com) and Delphi Automotive Systems LLC (Delphi), (www.delphi.com), as equal tiered technical leads, to develop an advanced, modular construction, inverter packaging technology that will offer a 30% cost reduction over conventional designs adding to the development of energy conversion technologies for cross-cutting applications in the building, industry, transportation, and utility sectors.

The proposed inverter allows for a reduction of weight and size of power electronics in the above-mentioned sectors and is scalable over the range of 15 to 500kW.

The main objective of this program was to optimize existing AeroVironment inverter technology to improve power density, reliability and producibility as well as develop new topology to reduce line filter size. The newly developed inverter design will be used in automotive and distribution generation applications.

In the first part of this program the high-density power stages were redesigned, optimized and fabricated. One of the main tasks was to design and validate new gate drive circuits to provide the capability of high temp operation. The new power stages and controls were later validated through extensive performance, durability and environmental tests.

To further validate the design, two power stages and controls were integrated into a grid-tied load bank test fixture, a real application for field-testing. This fixture was designed to test motor drives with PWM output up to 50kW.

In the second part of this program the new control topology based on sub-phases control and interphase transformer technology was successfully developed and validated. The main advantage of this technology is to reduce magnetic mass, loss and current ripple.

This report summarizes the results of the advanced modular inverter technology development and details:

(1) Power stage development and fabrication
(2) Power stage validation testing
(3) Grid-tied test fixture fabrication and initial testing
(4) Interphase transformer technology development

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1. Executive Summary

Current electric and hybrid electric vehicle systems comprise a number of separate elements supplied by a number of sources. These elements consist of propulsion motor inverter(s), generator inverters, DC-DC converters, accessory alternating current (AC) inverters, and extending to high power DC-DC converters for fuel cells, batteries, ultra capacitors, and specialized power conversion for flywheel applications.

The key issues identified by this industry are:

- Reliability
- High power density
- Low cost and easily producible
- Scalability

For automotive application, the other critical issue is the capability to operate under harsh environmental conditions like high ambient temperatures, high coolant temperatures, as well as excessive shock and vibration.

For the distributed generation applications, the key issues are:

- Poor requirement definition that results in frequent product retrofits,
- Immature manufacturing processes which do not incorporate a structured approach to product planning, quality control, manufacturing, or marketing, and,
- Outdated designs that do not include the newest architectures, packaging methods and technologies

The most serious issue for the inverter technology is the reliability. Mean time to first failure (MTFF) for typical inverters is estimated to be about five years. For inverters, low cost and high reliability are conflicting goals. Given the existence of a fielded product, there are three ways to improve reliability. One can over-design, implement redundancy, obtain a detailed knowledge of the product working-environment, its failure modes and mode causes and then feed this information back into product redesign. Both over-design and redundancy will result in increased cost. The third option requires large numbers of fielded product so that the failure mechanisms have an opportunity to occur, and can be identified and corrected. The proper integration of field data is the only option that does not increase the cost or complexity of the inverter.

Today's inverters are expensive due to the cost of the power electronics components. System designers must tailor the inverter for individual applications, whether vehicle or stationary. Thus, the benefits of mass production are not available. This leads to high initial procurement costs and high inverter maintenance and repair costs. In addition, the most critical power electronic components used in these inverters, Insulated Gate Bipolar Transistor (IGBT) modules, are all produced offshore with no domestic sources.

The solution to this problem is a low cost, modular, reliable, producible, and scalable inverter that can be used by both vehicle and distributed energy systems. Applications for this advanced inverter include:

- Electric propulsion systems for vehicles, ships, rail, both military and commercial;
- Power conditioning equipment for distributed energy systems using fuel cells, photovoltaic arrays, rotating generation equipment, etc.;
- Power processing equipment for industry such as electric welding and electroplating; and
- Variable speed drives for processing equipment, production lines, fabricating machinery, air compressors, etc. This includes capabilities for soft start as well as spike avoidance.

Recent efforts to rapidly expand the production of integrated inverters have not resulted in improved reliability. At this time the power electronics industry is uniquely positioned to develop a 'next generation' inverter that has a minimum of ten-year MTFF, better performance and lower cost. The recent advent of new technologies such as DSP (digital signal processing), the growth in sales to a few hundred thousand inverters, and the emergence of larger companies with interest in automotive and distributed generation inverters make this possible today.

This DOE sponsored program, allowed the following upgrades to be made to AeroVironment Inverter Technology:

- ***Size and weight improvements***. Power dissipation of each power semiconductor was increased by about 12%.
- ***Reliability improvement***. Elimination of the thermal pad, enhanced thermal cycling and lower thermal impedance of the IXYS semiconductor improves the inverter reliability.
- ***Cost improvement***. The latest analysis shows that the cost reduction of the improved inverter over conventional design approaches using conventional IGBT modules was increased by additional 10% due to direct component saving and the simplified assembly and verification process.

The new design developed in this DOE sponsored program is fully applicable for automotive and distributed generation inverters:

- The power stage and gate drives are capable to operating at temp up to 90C
- The inverter reliably operates with fluid coolant temp up to 90C
- The max output power level is 50kW (at 90C coolant) or 90kW (at 65C coolant)
- Inverter Voltage Bus: 400VDC
- Proved the operation at harsh automotive environment with excessive vibration and shock
- The neutral phase was added to the inverter for dist. generation applications
- The power stage interfaces with digital controller

The “Advanced Modular Inverter with Interphase Transformer Technology” has great opportunity to be commercialized. This initial product is targeted for automotive and distributed generation applications and would liberate significant space and weight that could be then used for other mission critical applications.

2. Program Objective

The overall objective of this program was to design, build, and test prototype inverter systems that are low cost, producible, reliable, modular, and scalable that can be used by both vehicle and distributed energy systems. Building on a successful history of power control and conditioning research and development programs, AeroVironment developed and tested a unique, advanced inverter packaging technology. This program leverages existing initial inverter packaging technology results to develop a low cost inverter, while providing the ability to operate in automotive under the hood environment and virtually no changes in production methods.

Thus, the objective of this research was to improve advanced inverter packaging technology to a pre-commercial stage that will allow for a reduction of weight and size of power electronics and is scalable over a wide power range of 30 to 500kW.

The program consists of two sections, each with specific objectives listed below:

Inverter Development/Grid Tied Test Fixture
The objective of the Inverter Development/Grid Tied Test Fixture phase of the project was to design, optimize and fabricate high-density power stages capable to operate at harsh environment at power 15-90kW. To prove the reliability power stages went through extensive verification testing: performance, durability and environmental. To further validate the design the other objective was to design, fabricate and verify the grid tied test fixture with the two developed earlier power stages for field-testing purposes.

Interphase Transformer (IPT) Development
For the Interphase Transformer phase of this project, the main objective was to design, develop and fabricate interphase transformers using custom ferrite cores. The existing inverter controls were modified to accept a new control scheme. Finally the IPT technology was validated through performance testing.

3. Inverter Development

3.1 Existing Inverter Technology Description

AeroVironment's existing inverter technology is a novel approach in packaging small power semiconductor devices, primarily discrete IGBTs (not modules) or MOSFETS, to provide a reduction in cost, weight, and size of a power electronics element. Our power switch building block may be combined in many configurations to form integrated power switching assemblies. This unique assembly comprises a heatsink, discrete power devices, and a power circuit board with bus bars and filter capacitors. Gate drive electronics (off-the-shelf) are located on the interface board directly above the switching elements. The analog controller for an integrated module assembly was an add-on module. This technology performs a similar function to that of an integrated IGBT power block module where many discrete chips are interconnected as an assembly.

Specific advantages of our packaged inverter are:
Size and weight advantage. The heatsink required for cooling the discrete IGBTs is a lightweight, thin-wall aluminum extrusion that passes cooling fluid and provides excellent thermal balance. Our inverters don't require the thick sections typically used in conventional IGBT modules for threaded fasteners or manifolding. In addition, a conventional IGBT module assembly incorporates an internal/intermediate copper heatsink, internal busbars, enclosure and encapsulation, all of which contribute to the excess weight and complexity of the module. Conventional IGBT modules must also be attached to a thick-walled secondary heat sink that adds weight and complexity to the overall system. Our approach places IGBT die in a "vertical" orientation similar to books on a shelf. Modules, however, place IGBTs horizontally, like books spread out on a table, i.e., a less efficient packaging configuration.

Flexibility advantage. Our advanced inverter packaging technology uses small, discrete power devices. Only as many devices as necessary need be used to meet power requirements. Providing power capability in small increments leads to reduction in cost, weight and size. This also allows configuration flexibility because the arrangement is not dictated by large, fixed IGBT module elements that have a preferred layout and interconnection scheme.

Scalability Advantage. Our advanced inverter packaging technology can be scaled over a wide power range of 30 to 500 kW. Liquid cooling is not practical below the 30 kW level. At present, an upper limit of scalability of 500kW is used for single assemblies (using high voltage discrete IGBTs). The upper limit is not dictated by the power, but by the length of the heatsink, bus bars and circuit board. These limits are established by physical constraints involving differential expansion of dissimilar materials and differences in the temperature of components. As we have discovered, problems occur even at the 250kW level, although this appears solvable. This limitation exists in one dimension only, thus allowing for commonality in all other dimensions.

Cost Advantage. Detailed analysis shows that our advanced inverter packaging technology offers at least a 30% cost reduction over conventional design approaches using conventional IGBT modules. Specific reasons for these cost savings are:

Lower Component Costs. The critical switching component, the mass produced discrete IGBT, is less expensive in discrete form than the integrated IGBT module in common use today. The performance of these mass-produced discrete IGBT power devices are also continually being upgraded to reduce costs as well as to allow higher voltage, current, switching speed, efficiency, operating temperature and thermal capability. Significantly, these upgrades are transparent to our design and application because the basic size and shape of the discrete IGBT device does not change. Thus, a production line is uninterrupted when required to incorporate a major performance or cost improvement to a specific discrete IGBT. In addition, the heatsink is a simple low cost extrusion rather than a complex integrated heatsink assembly.
Lower Assembly Costs. Assembly requires very little touch labor since the design focuses on automation including automatic machine insertion of components. The entire assembly combines discrete IGBT devices, busbars, capacitors, and other minor elements. It is wave soldered as the final, low-labor production process.
Commonality of Components and Design. Scalability allows for application flexibility without changes to design, production equipment and processes. The technology is easily expandable from low power and voltage to high power and voltage all using common hardware elements including heatsink, discrete IGBT devices, bus bars, spring clips, and power circuit boards.
Lower Packaging Costs. This technology is inherently lighter and smaller than conventional approaches. Thus, packaging is simplified, the envelope is smaller, and fewer materials are used.

Reliability advantage. Because of thermal issues, inverters using conventional IGBT modules require complex heatsinks that are difficult to build and have leakage problems. This degrades reliability. The heatsink design used in the advanced inverter packaging technology is very simple and easy to build. This, coupled with the advantage that the advance inverter packaging technology can be produced using automated assembly processes, offers an inherent reliability advantage.

Technology independence advantage. The discrete IGBT devices used in the advanced inverter packaging technology are produced by a number of U. S. manufacturers. This significantly reduces our dependence on foreign suppliers for such a critical technology. It also allows for a more competitive procurement of material that currently does not exist in the world marketplace.

The basic specification of the high voltage inverter developed by AV prior to this program

- Input voltage - 900 VDC
- Output voltage (at rated power) 630 volts rms
- Max continuous power - 210kW
- Fluid requirements <65C inlet
- Weight - 3.88 kg (» 45 kW/kg)
- Size (210kW) – 10.12” x 10.12” x 3.58”

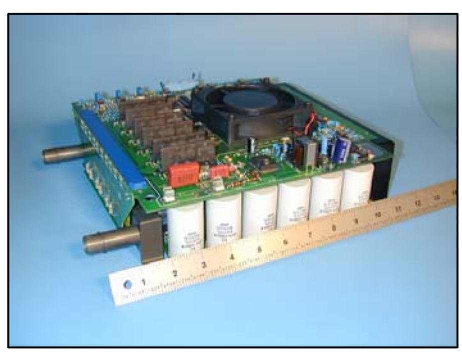


Figure 1. High voltage packaging technology

3.2 Limitations of the AeroVironment Inverter Technology

While this technology has many advantages, the existing high voltage inverter was not applicable to the automotive market. The original design effort concentrated on proving the novel packaging concept and operational functionality at normal ambient condition (25C). The inverter was always intended for the automotive market, however, prior to this program could not operate in harsh automotive environments. Limitations of the existing inverter technology are listed below:

- Too low operating temperature up to 55C – The temperatures under the hood are much higher than in other stationary applications and in close proximity to the switching elements may reach up 100C. The power stage capability to operate at this temperature (prior to this program) was limited mainly by the gate drive circuit. While the DSP controller could be located at some distance from switching elements in a separate compartment, the gate drives need to be as close as possible to the IGBTs. The existing gate driver modules that were available on the market were not as robust and capable to operate at high temperatures. During this program we recognized the need to develop new gate drive circuits that could operate at extreme temperatures, and are more reliable.
- Low fluid coolant temp <65C inlet – The ability of the inverter to share the coolant with engine and operate at elevated coolant temp (up to 100C) reduces the size of the overall package. This is a critical requirement for future combat vehicles and other program. Such a feature eliminates such sizable components as the heat exchanger and pump, and further improves power density and reliability of the system. All AV inverters prior to this program operated at a maximum coolant temperature of 65C. The maximum junction temperature of the switching elements always limited the operation at higher coolant temperatures.
- Too large a maximum continuous power 210kW – In typical automotive inverters, the power consumption is in the range of 25-100kW.
- Too high Voltage Bus: 800VDC – The standard voltage bus required in applications with engine or generator is approximately 400VDC. Such voltage level allows selecting components with max operating voltage of 600VDC. AV's prior inverters based on Alpha technology were designed and validated with higher voltage components (1200VDC).
- Not designed for vibration and shock requirements - The under the hood inverter is subjected to severe vibration and shock requirements. The frequency of applied vibration could vary between 10-1500 Hertz, at levels up to 5 g. The inverter and its mounting systems must also be capable of withstanding the shock of +/- 10.0 g in all three axes.

The main limitations of this technology in the distributed generation applications included:

- Lack of the neutral phase – The power stage prior to this program was developed as a motor drive and required only three phases. The basic requirement for the distributed generation application is the topology based in four phases (A, B, C) and Neutral. The existing power stage needs to be redesigned to operate for this application.
- Lack of the interface with digital controller - The power stage was only capable of operating with an analog controller. New interface circuitry and connectors need to be added to operate with our last DSP controller. In addition, the main requirement for the distributed generation inverters is anti-islanding protection. Due to safety reasons the inverter needs to be capable of disconnecting the load when grid connection is lost.

3.3 New Inverter Basic Specification

Inverter Basic Specifications are shown in Table 1

Specification	DOE - Alpha Inverter
Output Power Rating	50 KW
Max Output Power Rating (at 65C)	90KW
Phases	4
Switching Frequency	13 kHz
Cooling Type	Liquid
Input Type	Regulated DC
Input Voltage Min / Max	350 / 400 VDC
Input Current Continuous/Peak	150 ADC
Output Test Load Type	3 wire to resistive load
Nominal Output Voltage	208VAC
Output Current Continuous/Peak	180 Arms / 250 Arms
Output Frequency	60Hz
Power Amb Air Temperature Min/Max	-25C to +90C
Logic Amb Air Temperature Min/Max	+55C
Liquid Cooling Temperature Min/Max	+95C
Size	10"x10"x3"
Weight	3.5 KG

Table 1 New inverter specifications

The new power stage assembly is shown on below Fig 2

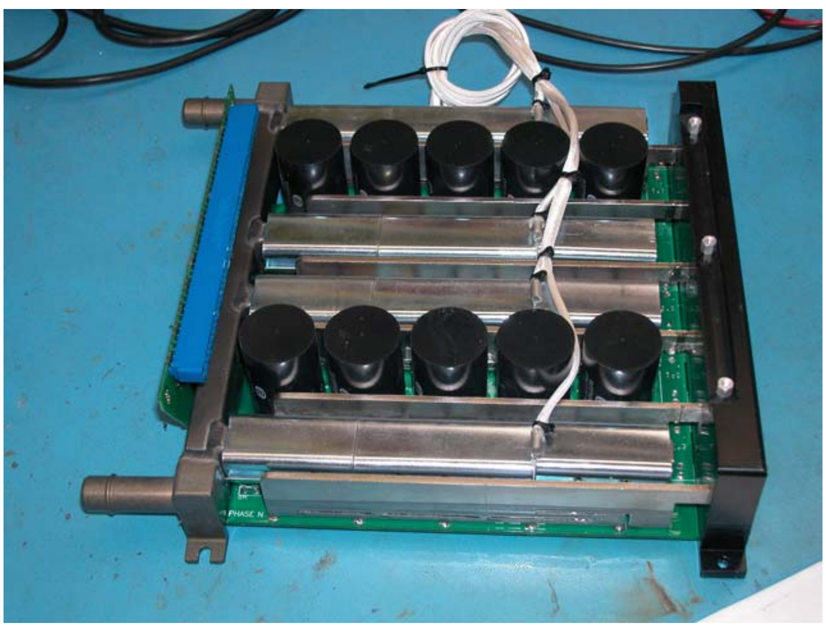


Fig 2. New 50kW automotive inverter

3.4 Detailed Developmental Tasks

Task 1.0 Finalize inverter requirements and select the inverter topology

The first task of this program was to finalize the basic requirements of the inverter and select the topology. Since the final field-testing was proposed to take place at the Delphi facility and Delphi had no need for just the power stages, several weeks were spent on selecting the inverter-based application that would accommodate Delphi needs. AeroVironment proposed several power processing solutions including: Regen-Dyno, ABC-150, and Grid-Tied Load (GTL) bank. Delphi decided to select Gird-Tied Load Bank with two alpha inverters that allow testing motor drives with PWM output up to 50kVA. This test fixture will operate with current up 180Amps rms (up to 280VAC) and simulate typical linear RLC household loads, saves energy by recycling it into utility and therefore reducing facility HVAC loads. Based on the AeroVironment topology for the higher power range inverters, AV reviewed all the necessary changes and optimizations schemes that were applicable for this application. We developed preliminary topology and packaging concept for the 50kVA liquid-cooled inverter. Significant time was spent reviewing detailed requirements for environmental, performance and durability tests. Finally, the topology and packaging concept of the inverter was selected.

Task 2.0 Major inverter components research and evaluations

After defining the topology and packaging scheme, a majority of the effort in the next task went to research the key power stage and interface PCB components. After extensive evaluation of the discrete power semiconductors, we selected the latest ISO-PLUS 247 transistor from IXYS. This new isolated IGBT not only provides a 2500V(RMS) isolation rating but also achieves lower junction to heatsink thermal impedance, lower junction to case capacitance and better thermal cycling when compared to conventionally isolated devices. The new IGBT from IXYS is shown below:

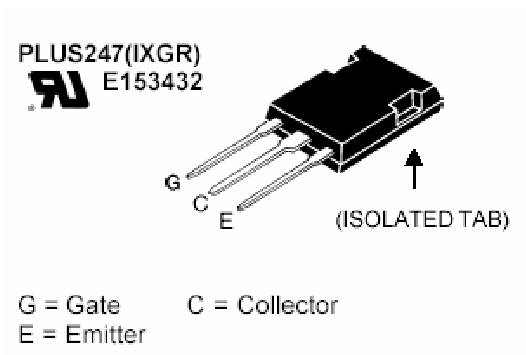


Fig 3. IGBT from IXYS

We also performed an analysis to optimize the Alpha heatsink. The thermal model of the existing heat sink was compared with a new model based on a modified extrusion with improved heat transfer cross-section. The results showed that the previous model was near optimal. As a result, the existing heat sink design was selected since only a few percent improvement in thermal transfer does not justify the extra cost and schedule risk to develop a new extrusion die.

Another vital element researched was the gate drive circuit required to switch the IGBTs. The desired circuit for this application must improve on a few important parameters such as high operational temperature (100C or higher), high dV/dT, fast rise/fall/propagation times and built-in protection. After extensive research, we concluded that off-the-shelf gate drives presently available do not meet desired requirements. The decision was made to develop a custom gate drive using off-the-shelf components with higher performance.

Task 3.0 Develop final mechanical and electrical drawings, BOM, schematics and layouts

During this task all the final designs and documentations were completed. The schematic, BOM and layout was finished for each of the following boards:

- Power PCB
- Interconnect PCB
- Interface PCB
- Gate drive

In the area of mechanical design all major mechanical components listed below were designed and documented.

- Buss bars
- Heat sink
- Manifolds
- Inlets and outlets
- Bus head top and bottom

More work was performed to validate our high temperature gate drive circuit. This circuit was designed to be a drop-in replacement for the Powerex driver 57962L. It was made to match or exceed the Powerex part specifically in speed, drive current and temperature range. Testing led to small changes in the design; some hysterisis was added to the UV comparator. Thermally the unit works within expectations. In addition the gate drive test fixture was designed, assembled and verified for faster gate drive validation.

Task 4.0 Procure all the major components, board level testing and fabricate the subassemblies

In this task all PCBs and components for each board and were procured for six systems. All the long lead components like IGBT and capacitors were also selected and procured. Next the PCBs for the first prototype (Power PCB, Interconnect PCB, Interface PCB) were populated and passed initial functional board level tests.

Ten Gate Drive PCBs were assembled and installed into the existing inverter fixture to conduct more performance tests with real loads to validate the gate drive circuitry.

The fabrication of all major mechanical components listed below was also completed:

- Buss bars – 41 pc were laser cut, bended per dwg, cleaned and zinc plated
- Heat sink extrusion – 24pc were machined for 6 sets
- Manifolds – 6 sets were machined

- Inlets and outlets - 6 sets were machined
- Bus head top and bottom – 6 sets were machined

First heatsink assembly was assembled, welded and passed leak test at 30psi. The first heat sink assembly was later anodized and was ready for final assembly with the IGBT and other PCBs. Next the assembly of the first liquid-cooled inverter was successfully completed. All the major components such as bus bars, capacitors, IGBTs, and gate drive resistors were soldered to a PCB and assembled with heat sink and clips.

After validation of the first inverter prototype the fabrication process was repeated for all the remaining inverter assemblies. Next, each of the inverters passed the final system acceptance test.

Task 5.0 Inverter performance system level testing

During this task the first high density power stage prototype passed the initial bench level open loop test. Next, the power stage was integrated with the DSP controller and iPower module, and set up as a power filter test fixture for closed loop system level testing. The system passed initial low power startup and functional tests. The new high temperature gate drive circuit integrated with the inverter was fully qualified and the test data recorded, including the waveforms. Next, the high power tests were successfully completed, validating the design and operation of a new high temperature gate drive circuits. After passing initial high power tests the performance test plan was completed.

The final performance verification tests at higher currents started per the performance test plan at ambient temperature (22C). The inverter was fully qualified at the DC bus level set to 350VDC. It successfully operated with current levels of: 100Amps, 140Amps, 180Amps, 200Amps and 250Amps. All the data and waveforms were monitored and recorded. Next, we repeated all the above the tests at the DC bus level setup for 400VDC. The elevated temperature test was also successfully completed with coolant temp up to 95C and current up to 156Amps. The inverter performance verifications tests were successfully completed and the results met the design objective.

The test results are shown in section 3.7

Task 6.0 Inverter durability tests

The inverter durability test plan and test procedure were completed. Per the plan, the inverter underwent 100hrs of cyclic stress tests (600-1200 cycles) to provide durability and lifetime estimates data. The setup for the inverter durability test was completed and the inverter durability test was successfully completed.

The test results are shown in section 3.8

Task 7.0 Inverter environmental tests

The inverter environmental test plan was developed and reviewed with the testing vendor. The inverter for this test was packaged in a enclosure with custom high-density liquid-cooled inductors and DSP controller The next step was to complete the wiring process and acceptance tests. Due to a program scope change, and the new objective to test inverter functionality not the enclosure, the following tests were not conducted: Fungus, Humidity, Dust, Cleaning Spray, Chemicals, Sealing, Salt and Fog.

The environmental tests comprised the following tests:

- Operating Temperature Test (24hrs) - The inverter was operated within the temperature of – 25 °C to + 25 °C and met the performance requirements specified in this document while continuously exposed to inlet coolant temperature up to +90 °C. The results of this test are shown in the appendix A.
- Thermal Cycling Tests (72hrs) - The inverter was operated within the temperature of – 25 °C to + 50 °C and met the performance requirements specified in this document while continuously exposed to inlet coolant temperature up to +90 °C.
  Two hours before the end of the cycling test, the inverter failed and the test was stopped. The cause of the failure was determined to be the failure of the laboratory flow switch of the external cooling system that was not correctly set up. The test was repeated and the test results are shown in appendix B.
- Vibration tests - The power stage successfully passed vibration tests. The inverter was installed on the custom 0.5" mounting plate without vibration mounts. The whole assembly was mounted on the vibration exciter. The control accelerometer was attached in the test fixture in the appropriate orientation to allow the vibration input levels to be monitored and controlled.
  The following tests were performed:
  Resonance Search Test - was performed in the X and Y Axes by slowly sweeping logarithmically from 20 to 500Hz at a level of 5g's. Resonances were defined at frequencies where the response/input ratio was 2:1 or greater.

  The three most significant frequencies and response g/s were found.

  Resonant Dwell - power stage was vibrated for one hour at each of the three most severe resonances in each of the X and Y Axes using the levels listed above.

  The power stage was inspected for any loose connection and did not show any visible damage.

  Narrowband random-on-random – the inverter was tested at random frequencies between 5-500Hz on the X-Axis. The unit successfully passed the first 45-minute tests (at 0.0075 - 0.2698g2/Hz) without any visible damage. After the next run at (0.0149 - 1.2746g2/Hz), we observed some loose components on the interface PCBA and the test was stopped. We will address this issue during next layout. The main power stage did not show any visible damage and will be shipped back to AV, assembled and we will verify the inverter operation.
  The test results from vibration tests are shown in the appendix C

- Shock test - The power stage successfully passed shock tests. The power stage was subjected to 3 shock pulses 10g's for 10mS in each direction. The power stage was shipped back to AV, assembled and functionality was verified.
  The test results from shock tests are shown in appendix D.

3.5 Gate Driver development and test results

Background
Over the last few years, we have recognized that reliable inverters need state-of-the-art gate drivers. Faster transistor devices and circuits, as well as extreme temperature requirements must be satisfied to remain competitive and keep the inverter near the leading edge of new technology development. The commercially available gate drive modules do not meet those requirements. The ideal gate driver must perform several basic functions to satisfy those needs.

Basic Driver Requirements
- It must translate a logic signal to a voltage and power level capable of driving all MOSFETS or IGBTs used in our designs.
- It must provide isolation between the logic source and the high voltage gate node.
- It must monitor and report the occurrence of a desaturation of the gated part and locally disable the gating of that part in a safe and expedient manner.
- It should monitor and report if the power supply for the gate circuit is out of a specified range and provide local driver disabling.
- It must incorporate a power source that provides isolated logic power for the gate drive circuitry.
- It should have a noise immune input for applications that require the controls to be some distance from the inverter or live in high EMI environments.
- It must have very precise and accurate timing characteristics.
- Initial design should provide form-fit-function replacement for existing drivers to aid in comparative analysis and apply to existing applications.

Desired specifications that need to be met is shown in below table 2;

	Specification	Desired Value	
1	Temperature Range	-40C to +100C	
2	Switching Frequency	100 kHz	
3	Propagation Delay	< 150 nSec	
4	Driver to Driver Edge Matching	< 50 nSec	
5	Rise and Fall time	< 20 nSec	
6	Gate Drive Current Peak	> 10 amps	
7	Input to Output Isolation	> 2500 Volts	
8	Common Mode dV/dT	> 50 V / nSec	

Package Design:

It was decided to design the new gate drive as a dropin replacement for the module previously used. This allowed testing capability in older equipment and substitution if desired. The new driver is a Form-Fit-Function replacement with improvements.

Standard Gate Drive Module: New Gate Drive Equivalent Circuit:

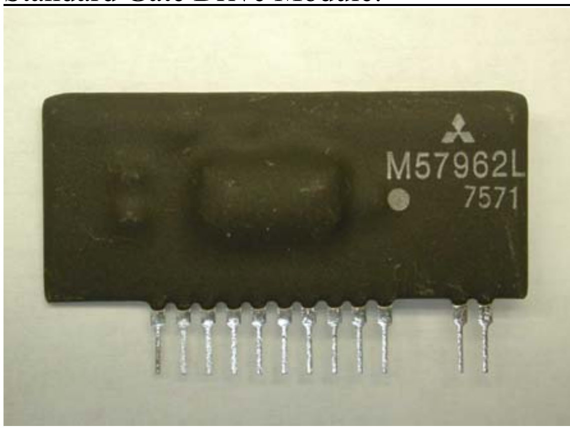


Fig 4 Standard Gate Drive Module:

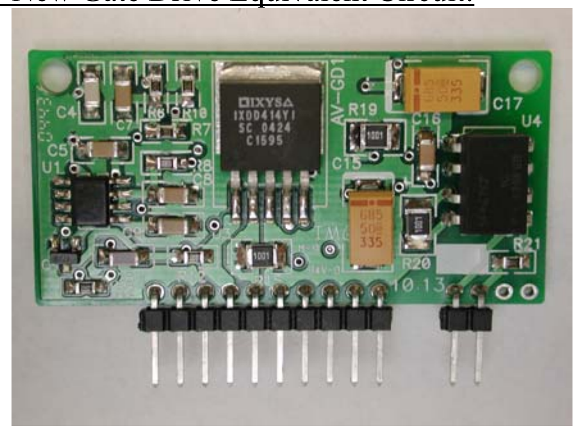


Fig 5 New Gate Drive Equivalent Circuit

Driver Test Setup (Fig 6)

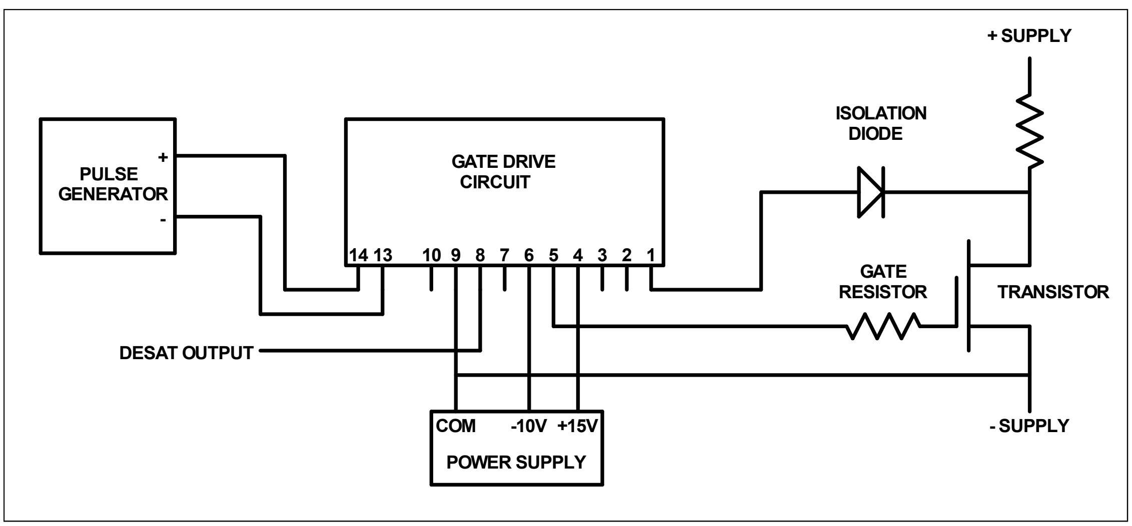
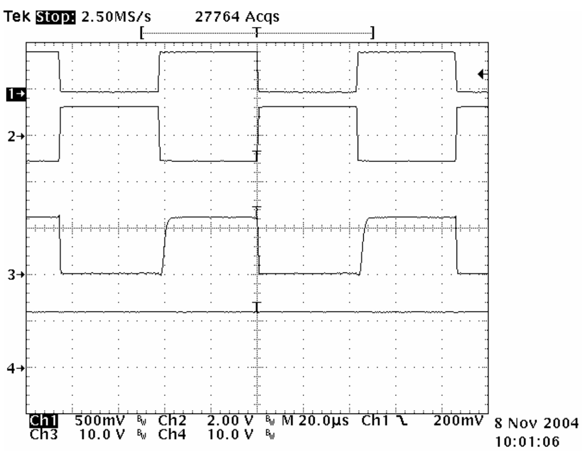


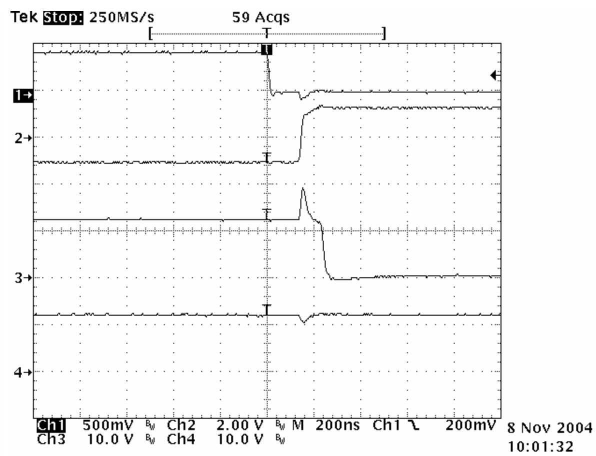
Fig 6 Gate Driver Test Setup

Driver Test Data
The following scope pictures show these gate driver signals.
Channel 1 is J1-13, the gate drive input signal, low is on.
Channel 2 is J1-5, the gate drive output signal, high is on.
Channel 3 is the collector of the driven transistor, high is open.
Channel 4 is J1-8, the Desat fault output signal, low is Desat.
Ground reference is the emitter of the driven transistor.
Picture 7 shows the normal gating function.

Picture 8 shows a close up of the turn on portion. The gate input goes low and 140 nSec later, the gate output goes high. 90 nSec later the transistor turns on. (the spikes are common mode noise in the test circuit)

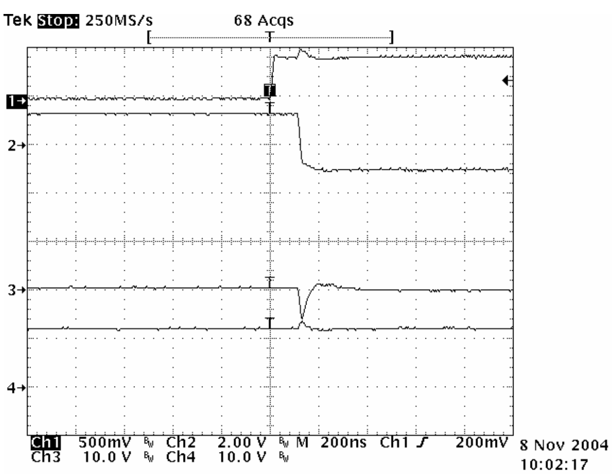
Picture 7: Picture 8:

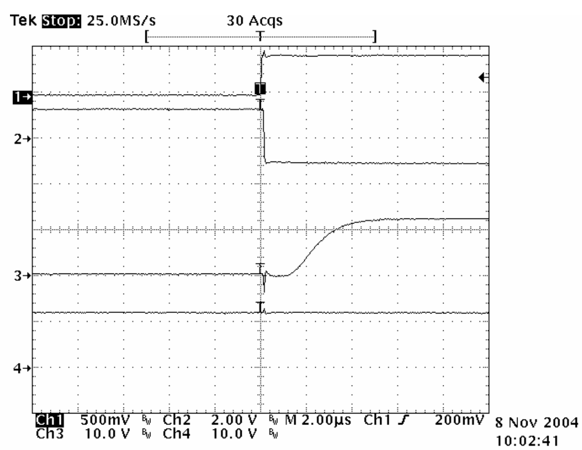




Picture 9, 10 shows a close up of the turn off portion. The gate input goes high and 120 nSec later, the gate output goes low. 10 nSec later the transistor turns off. (the spikes are common mode noise in the test circuit)

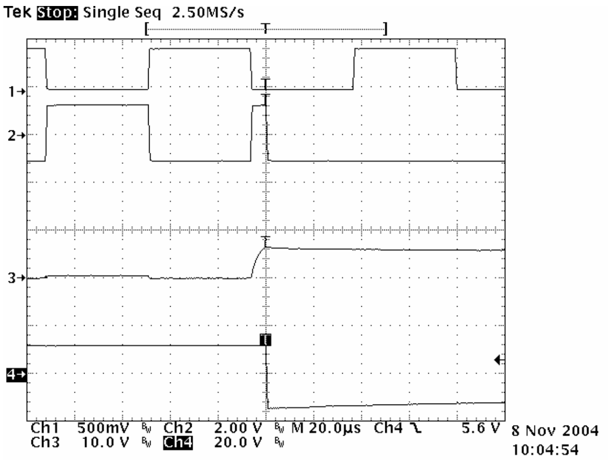
Picture 9: Picture 10:

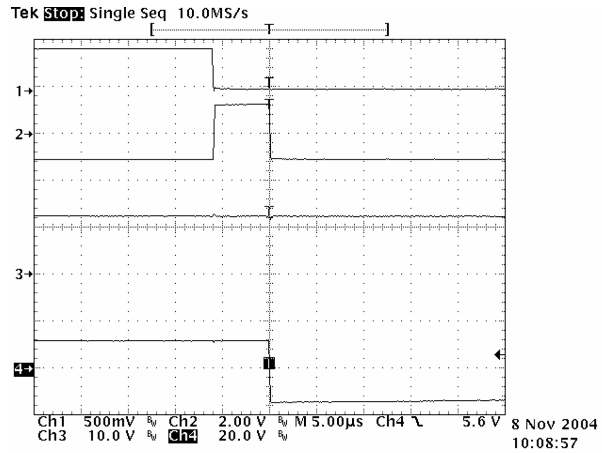




Picture 11, 12 shows a typical desaturation event. The collector is open before the gate is applied. The gate input goes low. Then the gate output goes high. 6 uSec later the Desat is detected and the output gating is disabled.

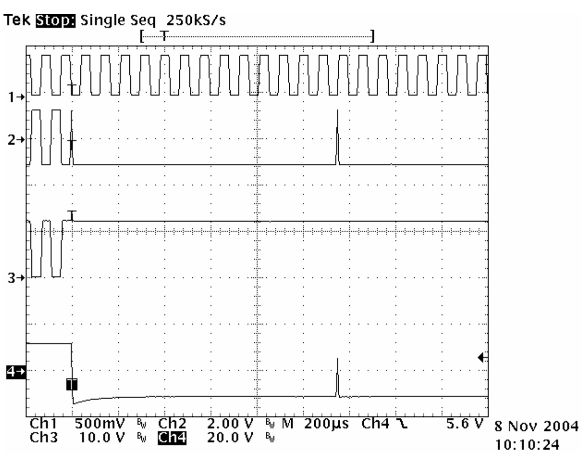
Picture 11: Picture 12:

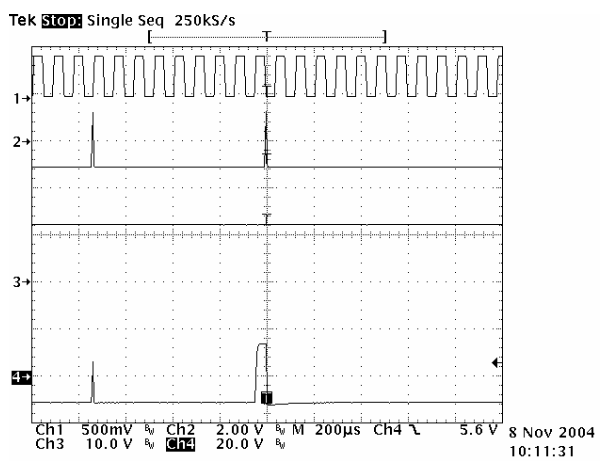




Picture 13, 14 shows repeating desaturation events. The collector is maintained open. The gate input goes low. Then the gate output goes high. The Desat is detected and the output gating is disabled. Input gating is allowed to continue. After the disable time period is over, the gating passes through again and trips a new Desat event. This will repeat every 1.1 mSec until the gating is externally stopped.

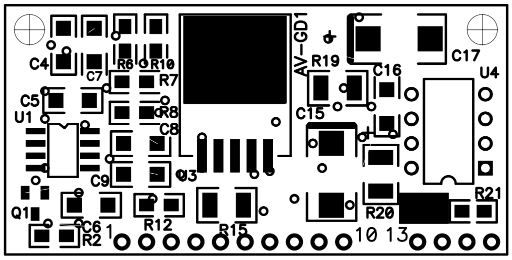
Picture 13: Picture 14:





Gate Drive Assembly is shown on below fig 15 and 16

New PCB Top **New PCB Bottom**



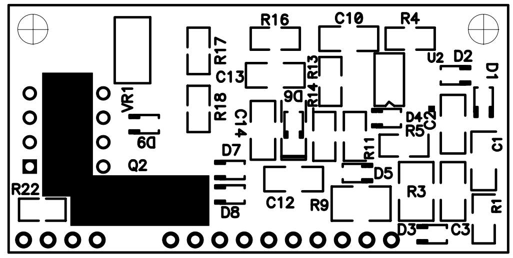


Fig 15. New gate diver assembly layout

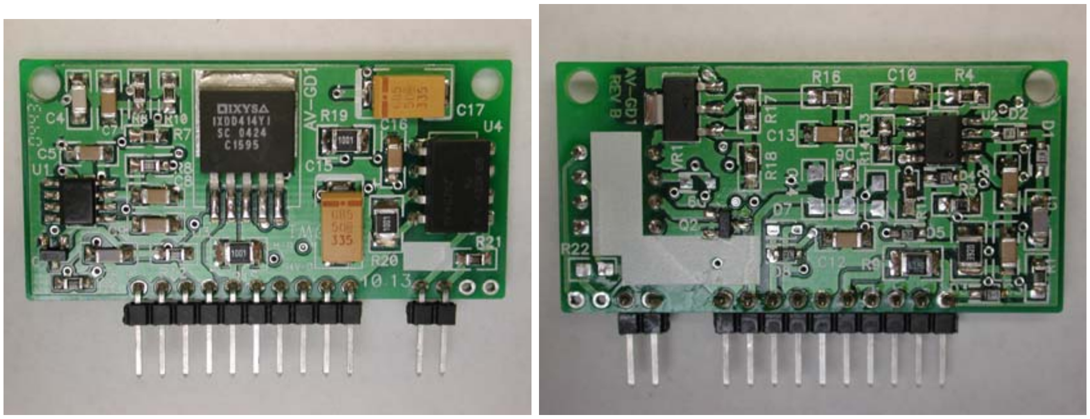


Fig 16. New gate diver assembly pictures

3.6 Inverter performance test results

New inverter architecture

The Alpha series of inverters is designed to have high power density and lower mass. This is accomplished by using discrete power transistors and a unique liquid cooled heatsink design. The new power stages architecture includes four poles, each being composed of parallel-connected IGBTs (ten low-side and ten high-side IXYS IXGR60N60B2D2). The DC bus is supported by ten parallel-connected Electronic Concept 30 uF, 600volt capacitors (UP36BC0300). All the power devices are through-hole, soldered components. Surface mount resistors are used for gating needs. Power connections to the inverter are made through soldered-in bus bars. The overall design is compact, volume efficient and structurally very ridged.

As the optimization of the new Advanced Modular Inverter progressed, it was apparent that existing gate driver modules that were available on the market were not as robust and capable as should be expected. As a result, it was decided that a new gate drive module must be developed which would match the new inverter technology and extend its usefulness as a system.

Inverter Test Purpose

The purpose of the following tests was to confirm functional operation and performance of the new high-density inverter and to experimentally determine steady state power capabilities under different points of operation.

Performance Test Setup

- DC Power Supply (capable of 300 ADC @ 400 VDC)
- Filter Inductors (four filter inductors rated for 300 A rms. iPower inductors or equivalent are recommended)
- Filter Capacitors (four filter capacitors suitably rated for filtering PWM.
- Resistive Load (configured as balanced WYE with neutral included; resistance range such that load can be varied between 20 kW and 150 kW when the phase to phase voltage is maintained at 208 VAC RMS)
- Fluid Circulating and Cooling System (flow rate up to 5 GPM with pressure drop of 1 PSI. Cooling capability at least 200 W / C)

- Current Sensors (four DC type current sensors, each capable of 400 A peak with accuracy of at least 1% of full scale; offset no greater than 1 A)
- Temperature Sensors (five J-type temperature sensors)
- Flow Sensor (fluid flow sensor capable of measuring flow rates up to 10 GPM)
- Control System (suitable for generating 13 kHz toggle signals for each of the four Alpha power poles. Controls will be operated closed-loop with interface to the internal current sensors. Modulation will be 60 Hz sine. Control system also provides enable and provides disable in response to desaturation, over-temp, over-bus voltage and over-current conditions. Neutral PWM is provided such that third harmonic injection is included.)

Test Configuration diagram is shown on below Fig. 17

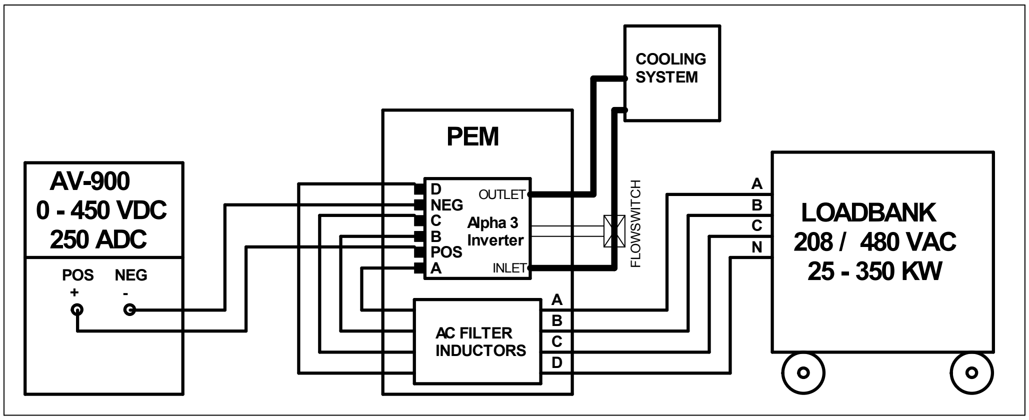


Figure 17.Inverter Performance Test Setup

1. DC supply is connected to Alpha DC port
2. Control System connected to Alpha Power Stage
3. Inductors (side A of each) are connected to Alpha phases A, B, C, and N
4. WYE-connected resistive load is connected to above inductors using four-wire connection
5. Fluid Circulating and cooling system is connected to Alpha heatsink
6. Current sensors are applied to negative DC bus, Phase A, Phase B, and Phase C
7. Flow sensor is connected in series with coolant line
8. Temp sensor 1 placed for sensing ambient temp.
9. Temp sensor 2 placed for sensing inlet temp.
10. Temp sensor 3 placed for sensing outlet temp
11. Temp sensor 4 placed for sensing IGBT temp.

Inverter Test setup pictures are shown below in Fig. 18 to 20.

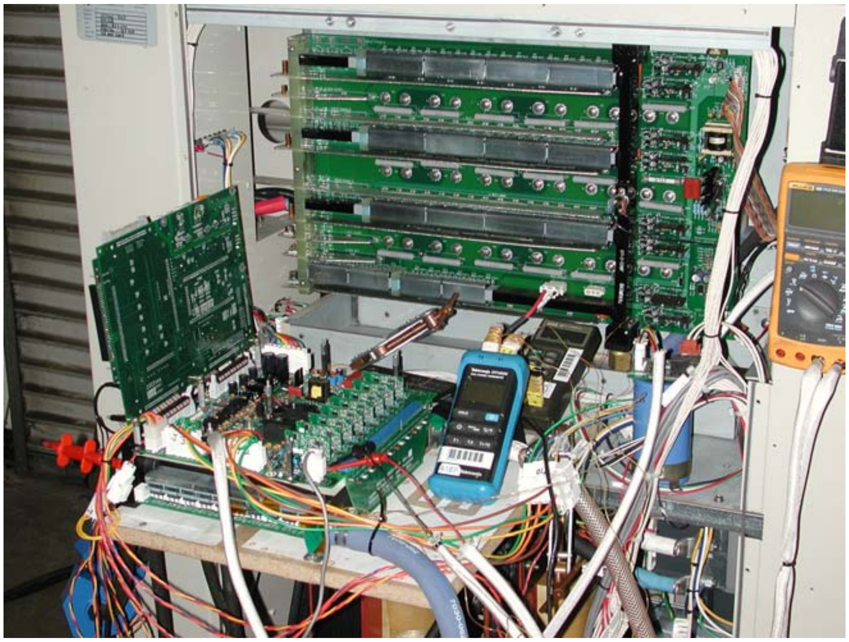


Figure 18. Inverter Test Setup for performance tests

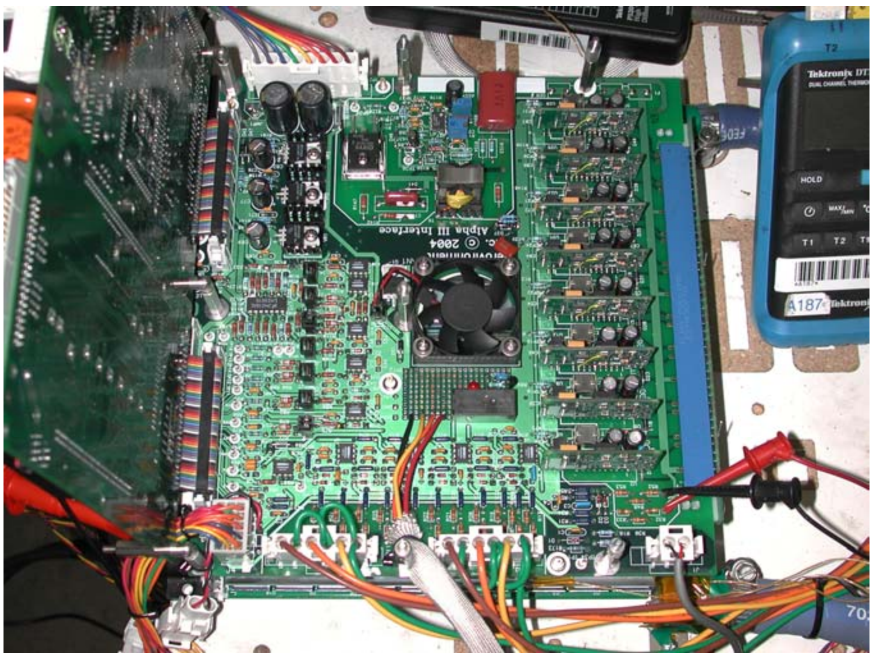


Figure 19. Inverter test setup - Interface Board view

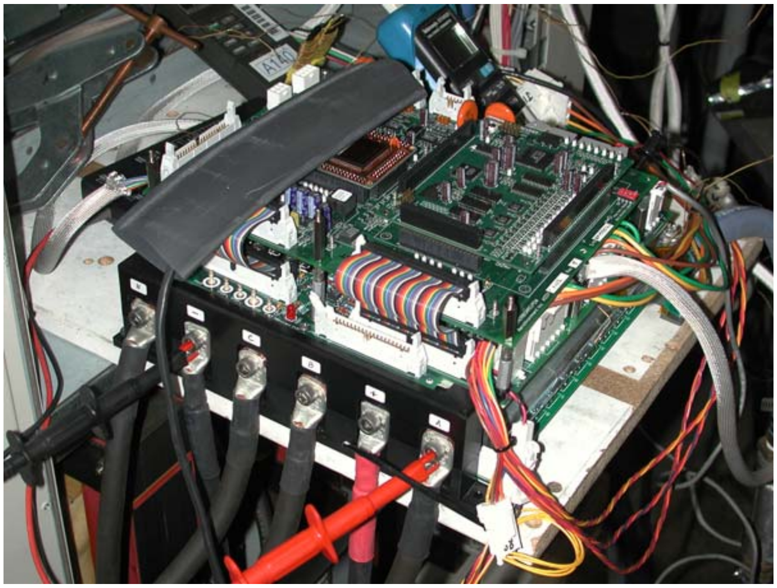


Figure 20. Inverter test setup – power connections

Following information during the test

- DC bus voltage
- Phase A to phase N RMS voltage
- Phase B to phase N RMS voltage
- Phase C to phase N RMS voltage
- DC bus current
- Phase A RMS current
- Phase B RMS current
- Phase C RMS current
- Ambient temp.
- Fluid inlet temp.
- Fluid outlet temp.
- Bus capacitor temp near phase A
- IGBT temp.

Performance Test Procedure

After basic functioning of the inverter unit has been confirmed, the following tests procedures are to be performed to verify the performance:

1. Turn on the cooling system at a flow rate of >2 GPM.
2. Set the output load for no loading value (High impedance).
3. Set DC bus power supply voltage for 350 V and current max of 20 Amps
4. Enable the unit and confirm no faults exist.
5. Apply load until the measured Phase A current is 100 A rms
6. Read data at 5 and 10 minutes of operation
7. Apply load until the measured Phase A current is 140 A rms
8. Read data at 5 and 10 minutes of operation
9. Apply load until the measured Phase A current is 180 A rms

10. Read data at 5 and 10 minutes of operation
11. Apply load until the measured Phase A current is 200 A rms
12. Read data at 5 and 10 minutes of operation
13. Apply load until the measured Phase A current is 250 A rms
14. Read data at 5 and 10 minutes of operation
15. Set DC bus voltage for 400 V
16. Apply load until the measured Phase A current is 100 A rms
17. Read data at 5 and 10 minutes of operation
18. Apply load until the measured Phase A current is 200 A rms
19. Read data at 5 and 10 minutes of operation
20. Apply load until the measured Phase A current is 250 A rms
21. Read data at 5 and 10 minutes of operation

<u>Performance Test Data</u>

Table 3: Test Data for procedure step 5
Coolant flow = 3 GPM - DCV = 350 V - Load = 100 Amps / 36 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	349	109	120	120	120	102	102	101	21	22.7	23.8	23.6	23.5
5 Min	349	109	120	120	120	102	102	101	22	26.6	27.6	32.8	26.3
10 Min	349	109	120	120	120	102	102	101	22	27	28	33.2	28.3
15 Min	349	109	120	120	120	102	102	101	22	27.2	28.2	33.5	29.3
20 Min	349	109	120	120	120	102	102	101	22	27.5	28.5	33.6	30.4

Table 4: Test Data for procedure step 7
Coolant flow = 3 GPM - DCV = 350 V - Load = 140 Amps / 50.4 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	348	149	120	120	120	140	140	139	22	28.5	30	37.3	30.9
5 Min	348	149	120	120	120	140	140	139	22	29	30.3	38	31.8
10 Min	348	149	120	120	120	140	140	139	22	29.8	31.3	38.6	33.9

Table 5: Test Data for procedure step 9
Coolant flow = 3 GPM - DCV = 350 V - Load = 180 Amps / 64.8 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	348	193	120	120	120	180	180	179	23	31	32.7	42.8	31.8
5 Min	348	193	120	120	120	180	180	179	23	31.6	33.2	43.7	35.4
10 Min	348	193	120	120	120	180	180	179	23	31.6	33.3	43.6	37

Table 6:Test Data for procedure step 11
Coolant flow = 3 GPM - DCV = 350 V - Load = 200 Amps / 73.8 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	348	220	120	120	120	206	205	204	20	25	27	37.6	23.7
5 Min	348	220	120	120	120	206	205	204	20	29.8	31.9	43.8	28.4
10 Min	348	220	120	120	120	206	205	204	21	31.3	33.3	45.6	33.4

Table7: Test Data for procedure step 13
Coolant flow = 3 GPM - DCV = 350 V - Load = 250 Amps / 90KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	348	265	120	120	120	249	250	250	21	34.3	36.8	52.4	37.7
5 Min	348	265	120	120	120	249	250	250	21	34.9	37.3	53.4	41.5
10 Min	348	265	120	120	120	249	250	250	21	35.4	37.6	54.1	44.8

Table 8: Test Data for procedure step 16
Coolant flow = 3 GPM - DCV = 400 V - Load = 100 Amps / 36 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	400	94.5	120	120	120	102	100	100	21	28.7	29.6	35.9	41.6
5 Min	400	94.5	120	120	120	102	100	100	21	28.4	29.4	35.3	40.4
10 Min	400	94.5	120	120	120	102	100	100	21	28.4	29.3	35.5	39

Table 9: Test Data for procedure step 18
Coolant flow = 3 GPM - DCV = 400 V - Load = 200 Amps / 73.8 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	400	188	120	120	120	200	200	199	21	33	35.1	47.9	41.9
5 Min	400	188	120	120	120	200	200	199	21	33.4	35.3	48	44
10 Min	400	188	120	120	120	200	200	199	21	33.4	35.4	48.2	44.1

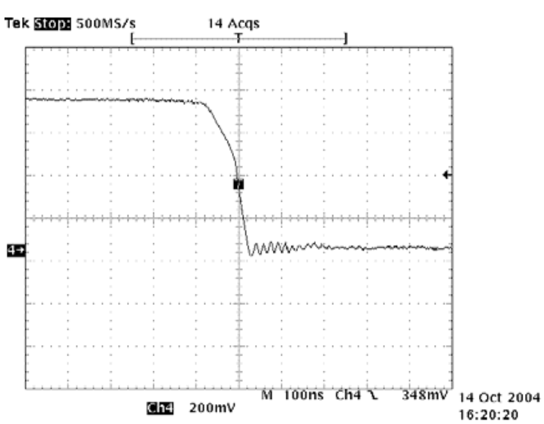
Table 10: Test Data for procedure step 20
Coolant flow = 3 GPM - DCV = 400 V - Load = 250 Amps / 90 KW

Time	DCV	DCI	Va-n	Vb-n	Vc-n	Ia	Ib	Ic	T amb	T in	T out	T igbt	T cap
0	399	232	120	120	120	249	250	250	21	34.5	36.9	52.5	35.5
5 Min	398	232	120	120	120	249	250	250	21	35	37.5	53.7	42.1
10 Min	398	232	120	120	120	249	250	250	21	35.6	37.9	54.5	45.4

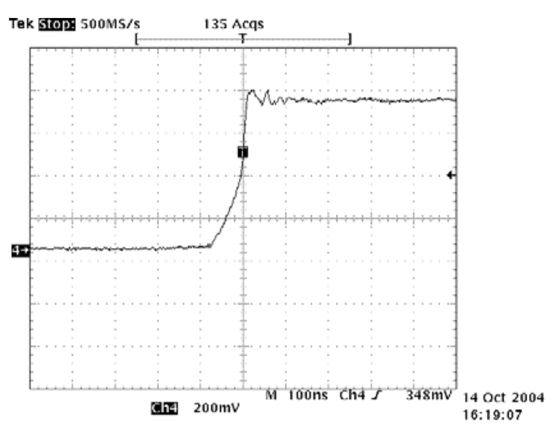
Picture 21 shows the C phase lower transistor turn-on with 100 amp loading on the AC output.
Picture 22 shows the C phase lower transistor turn-off with 100 amp loading on the AC output.

Channel 4 is the C phase inverter output. An isolated differential probe was used. Scale is 50 volts/div. Ground reference is the negative DC bus.

Picture 21:

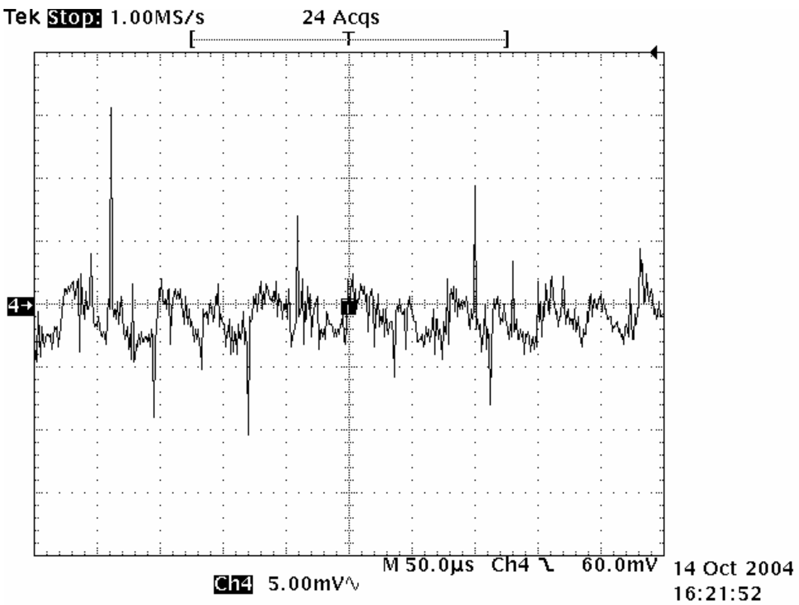


Picture 22:



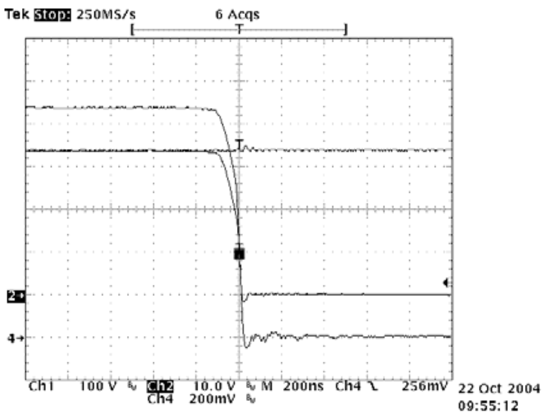
Picture 23 shows the switching ripple on the 350 volt DC Bus with 100 amp loading on the AC output. Channel 4 is the DC Positive Bus. An isolated differential probe was used. Scale is 2.5 volts/div Ground reference is the negative DC bus.

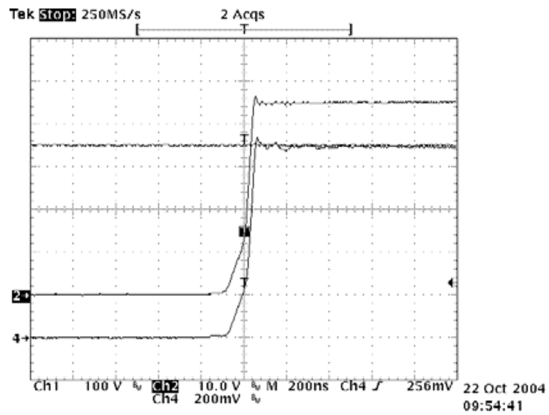
Picture 23:



Picture 24 shows the A phase lower transistor turn-on with 208 amp loading on the AC output and 450 vdc bus.
Picture 25 shows the A phase lower transistor turn-off with 208 amp loading on the AC output and 450 vdc bus.
Channel 1 is the A phase inverter output. An isolated differential probe was used.
Channel 2 is the A phase inverter output. A direct probe was used.
Channel 33 is the A phase inverter output. A direct probe was used. Scales are 50 volts/div. Ground reference is the negative DC bus.

Picture 24: **Picture 25:**





<u>Inverter Performance Test Data at high coolant temp</u>

High Coolant temp test condition (Table 11)

DC bus (VDC)	401.3
Load Current (AC Amps)	156
Output Power (kW)	56
T ambient (C)	19C
V output AN (AC Volts)	121
Coolant Flow (GPM)	3.4

High Coolant temp test result (Table 12)

Time	Tin	Tout	Tq	Tc	
11:30	27.2	27.2	27.5	26.4	
11:45	61.8	63.6	71.4	40.9	
12:00	79.8	81.9	89.5	53	
12:15	93.6	95.2	102.6	64.8	
12:30	94.7	96.2	103.2	66.8	Stabilized
14:30	94.6	96.1	103.1	66.9	

Tin Coolant inlet temp
T out Coolant outlet temp
Tq IGBT temp
Tc Capacitor temp

Inverter Performance Test Data Analysis

The following table 13 shows results from the performance test data. Generally, readings should be accurate within 1%.

#	Item	350 VDC Buss					400 VDC Bus		
	Test Step	5	7	9	11	13	16	18	20
1	Load Current (AC Amps)	102	140	180	205	250	101	200	250
2	Input Power (Watts)	38041	51852	67164	76670	92220	37800	75012	92336
3	Output Power (Watts)	36720	50040	64800	73800	90000	36360	72000	90000
4	Inverter & AC Filter Efficiency (%)	96.5	96.5	96.5	96.3	97.6	96.2	96.0	97.5
5	H2O Trise in degrees (C)	1	1.5	1.7	2	2.3	1	2	2.4
6	H2O Thermal Loss (Watts)	922	1383	1568	1844	2121	922	1844	2213
7	H2O Thermal Loss (%)	2.4	2.7	2.3	2.4	2.3	2.4	2.5	2.4
8	IGBT - H2Oin Temp. Delta (C)	6.2	9.0	12.0	14.3	18.7	7.1	14.8	18.9

Table 13 Results form performance tests

Thermal Losses Calculation (Line 6):

The Coolant type is Shell, Rotella ELC, CAT-EC-1, 50/50 with a specific gravity of 1.06. For simplicity, the coolant is referred to as 'H2O' in this report.

1 GPM = 3.785 LPM = 3785 Grams/Min

Flow = 3.3 GPM = 3.3 x 3.785 LPM = 12490 Grams/Min

Grams/Min x degrees C rise = Calories

12490 Grams/Min x 1 degree C rise x 1.06 = 12490 Cal/Min =220 Cal/Sec

Calories/Sec x 4.185 = Watts

220 Cal/Sec x 4.185 = 922 W

H2O Thermal Rise (C/W) = 1 / 922 = .0011 C/W @ 3.3 GPM

Heatsink Thermal Stability Time (Line 8):

The low heatsink mass and short thermal path from transistor to liquid allows fast thermal stability. The first data sample (Step 5) took over 20 minutes to show thermal stability of the transistor verses the water inlet temperature. Thermal stability is reached within 5 minutes of load being applied. Additional thermal readings show the same temperature delta. Stable thermal data can be taken within 10 minutes of a load or coolant temperature change.

Performance test summary:

The test data shows the inverter meet the design objective. It successfully operated up to 90kW at coolant temp below 65C and up to 56 kW at coolant temp up to 95C.

The test data shows also several defining characteristics of the new inverter design. First, it shows high efficiency from low to high load. These numbers represent the efficiency of the combined Inverter and the AC output filtering inductors. The inductor losses are not presented here but generally comprise about one percent of efficiency loss. So the raw inverter efficiency is about one percent higher than the shown values. The measured efficiency at full load is therefore 98.5%.

Second, the low thermal mass allows fast thermal stability but more importantly, it means that the thermal recovery from a high heat condition can be fast. Cool down time is shortened. The heatsink design has a short thermal path and low thermal resistance to the coolant.

3.7 Inverter reliability test results

The inverter reliability test consisted of two cycling tests conducted in AV facility.
Load Cycling Test – the inverter underwent 100hrs of cyclic stress tests (600-1200 cycles) from low load (5kW) to full load (56kW). The load was switched every 10min for 2.5 weeks.

Test data during the reliability test (Table 14)

	5kW	56kW
DC bus (VDC)	400.1	400.1
Load Current (AC Amps)	42	155
Output Power (kW)	5	56
T ambient (C)	22C	22C
V output AN (AC Volts)	120	120
Coolant Flow (GPM)	3.3	3.3

Temp Cycling Test – the inverter underwent 40hrs of temp cyclic stress tests operating at full load (56kW). The coolant temp was cycling from 30C to 95C every 1hrs for one week.

The inverter durability test was successfully completed without any failure.

3.8 Inverter FMEA

The FMEA was conducted and the results are shown in the below table 15

ITEM FUNCTION	POTENTIAL FAILURE MODE	POTENTIAL EFFECT(S) OF FAILURE	SEV	CLASS	POTENTIAL CAUSE(S)/MECHANISM(S) OF FAILURE	OCCUR	CURRENT DESIGN CONTROLS	DETECT	RPN	RECOMMENDED ACTIONS
IGBT Assembly										
	Single IGBT open	Temp rise	1		Faulty device	2	No detection	10	20	None
	Single IGBT short	Cascade failure	8		Faulty device, Too high current	3	High current detection by LEM	1	24	None
DC Bus Caps	Fail Open	More Ripple	2		Component failure,	2	UV bus voltage sense detection	1	4	None
	Fail Short	DC UV	8		Component failure	2	Ac OC detection	2	32	None
Clamping Diode	Diode Open	Reduced power, excessive ripple	5		Open device / connections	2	No detection	10	100	None

	Diode Short	Reduced power, excessive ripple	5		Device short	2	DC buss UV sensed under load	9	90	None
AC current sensors and circuitry	No current feedback (zero current)	Out of control	8		Connection or component failure	3	Over voltage protection in hardware and software	2	40	None
	Full scale signal	Out of control	8		Component or connection failure	2	Over current protection in hardware and software	1	16	
AC filter Caps	Fail open	Med Input THD	4		Component failure	2	No Detection	10	80	None
	Fail short	Med Input THD	8		Component failure	2	NO detection, PP will detect it	5	80	None
Input EMI filter	Internal cap failure Open or short	EMI out of spec.	3		Component failure	2	NO detection,	10	60	None
Contactor K1	Contact weld 1 phase	Forward feed from Utility	9		Component failure	1	No Detection	10	90	None
	Contact cannot close 1 phase	High THD	2		Component failure	2	Ac UV detection	4	8	None
AC voltage sense feedback	Open (zero volts)	Loose of controls	8		Component failure	3	AC UV sense, Out of synch fault	1	24	None
Temperature sensors and circuitry	OT sensed all the time	Unit won’t start	8		Component failure	4	Multiple detection	1	32	None
	OT not sensed	Unit could overheat	8		Component failure	4	Multiple detection	1	32	None
Cooling system	Heat Sink Fan Failure	Inverter Over Temp	5		Component failure	5	Temp detection	1	25	None
	Blocked Air inlet	System Over Temp	5		Snow , leafs	5	Multiple Temp detection	1	25	None
	Stir Fan failure	Inductor Over Temp	5		Component damage	5	Indirect multiple detection	2	50	None

3.9 Inverter development summary

In summary DOE funds allowed for the optimization and improvement of the advanced modular inverter technology. This was an important step in demonstrating to potential end users that the technology delivers meaningful value to their systems.
Specifically DOE program allowed us to eliminate all the limitations listed in section 3.3 for automotive and distributed generation inverters:

- The power stage and gate drives are capable of operating at temperatures up to 90C.
- The inverter reliably operates with fluid coolant temperatures up to 90C.
- The maximum output power level is 50kW (at 90C coolant) or 90kW (at 65C coolant).
- Inverter Voltage Bus: 400VDC.
- The operation was proven under harsh automotive environments with large vibration and shock.
- The neutral phase was added to the inverter for distributed generation applications.
- The power stage now interfaces with the digital controller.

<u>This program provided additional upgrades to AeroVironment Inverter Technology</u>

Size and weight improvements. One of the major improvements was selecting the latest IGBT ISO PLUS 247 from IXYS. The new part offered isolation up to 2500V RMS, eliminating the need for the thermal pad used to insulate the power devices from the fluid-cooled heatsink. In the design prior to this program, approximately 22% of the total thermal resistance between semiconductor junctions and ambient was due to the thermal pad. The new IGBT has much lower junction to heat sink thermal impedance therefore the power dissipation of each power semiconductor was increased by about 12%. This means that the through-power was increased by approximately 10%, which means that the power density of inverter units was increased by approximately 10%. In addition the new semiconductor has higher current rating (up to 75Amps at 25c) further improving the specific power therefore the size and weight.

It must be noted that despite adding neutral phase (extra heat sink, IGBTs, bus bar) the new power stage is smaller and lighter that the high voltage one. The new inverter has the highest known power-to-size and power-to-weight ratio.

Reliability improvement. The biggest reliability improvement comes from the elimination of the thermal pad, which was the reason for frequent failures due to isolation breakdowns. Enhanced thermal cycling and lower thermal impedance of the IXYS semiconductor adding up to the higher inverter reliability. Additional improvements come from the other important inverter component; capacitor. The new capacitors (Electronic Concept) have much operation higher temperature (105C) and are designed to withstand excessive vibration. Further reliability improvements are due to the gate drive circuit. The newly developed circuit has the ability to operate at a wider temperature range (–40C +100C), and higher switching frequency (e.g., 100kHz). It monitors the occurrence of a desaturation of the gated part and locally disables the gating in a safe and expedient manner. It has very precise and accurate timing characteristics and improved noise immune input for operations in high EMI environments. In addition, it monitors and reports if the power supply for the gate circuit is out of a specified range and provides local driver disabling.

Cost improvement. The latest analysis shows that the cost reduction of the improved inverter over conventional design approaches using conventional IGBT modules was increased by an additional 10%. The main reason for cost savings is the combination of lower components cost (IGBT) and improved power density. The performance of discrete power devices was significantly improved allowing for higher current and thermal capability while reducing the cost of this component.

The additional cost improvements are due to the elimination of the thermal pad. The direct component saving and the cost reduction are due to the simplified assembly and verification process.

4. Grid Tied Load Test Fixture (GTL-50)

4.1 Development Task

The development of the grid tied load fixture started by finalizing the major system level and software requirements. The software SRS were completed and the majority of the algorithms were developed and reviewed. The existing DSP software was modified and successfully tested on the bench using the new GTL controller. Next, the system schematic and BOM were completed and, after an internal design review, all major components were procured. In addition, the packaging layout was completed and verified with CAD software. Next, the assembly and fabrication of the Grid-Tied Load Bank was completed. The performance acceptance verification tests of the Grid-Tied Load Bank were started in January 2005 and were completed in March 2005. Currently the Grid-Tied Load Bank is located at Delphi's facilities.

4.2 GTL 50 Product Specification

- Replace Large RLC Load Banks
- Energy Savings
- Reduce Facility HVAC Loads
- Programmable current and PF
- Easy Programmable Controls
- Smaller Size and Weight
- Reduce installation cost (indoor)

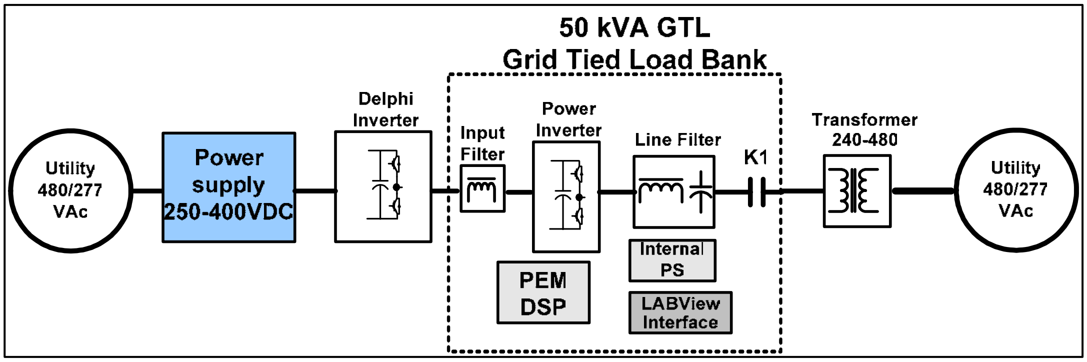
The GTL Series is AeroVironment's advanced next generation power electronics based grid tied load bank. It's capable of simulating resistive, inductive and capacitive loads. GTL saves energy by recycling it into utility and reducing facility HVAC loads. This device simulates typical linear RLC household and commercial loads.

Common Features

- *Capable of 50 kW resistive load or*
- *Capable of 50kVars inductive or capacitive **
- *Tied to the grid at 480Vac (50/60hz)*
- *LabView interface through serial RS-232 or CAN*
- *Optional Transformer Isolation*

4.3 GTL System Diagram

GTL System Diagram is shown on below Fig 26



4.4 GTL Basic Parameters

GTL Basic Parameters are shown in below Table 16

Item	Specification	Delphi -GTL
1	Application	Grid Tied Load Bank
2	Output Power Rating	50 KW / 50KVA
3	Topology	Alpha
4	Phases	3
5	Switching Frequency	15 kHz
6	Cooling Type	Liquid/air
9	Delivery Date	ASAP or 02-2005
10	Input Type	PWM inverter
11	Input Voltage Min/Max	250V to 400VDC peak
13	Input Frequency	20% to 100% PWM
15	Output Type	Delta Utility/xfmr
16	Output Voltage Min/Max	240VAC +/- 10%
17	Output Current Continuous/Peak	180 Arms / 250 Arms
18	Output Frequency	60 Hz
20		
21	Power Amb Air Temperature Min/Max	+25C
22	Logic Amb Air Temperature Min/Max	+25C
23	Liquid Cooling Temperature Min/Max	+65C
41	Control Interface	RS-232 or CAN

4.5 GTL 50 Acceptance Test Report

This report summarizes the testing that was performed at ESDC for the GTL-50. It includes waveforms and data that were collected during several weeks of testing in 2005. A picture of the GTL-50 is shown in Figure 27.

Figure 27 Grid Tied Load Test Fixture - DLS-50

Physical/Mechanical size: 45.5" x 25.5" x 54.5"

<u>Verification test setup</u>

Test set-up diagram is shown in Fig 28

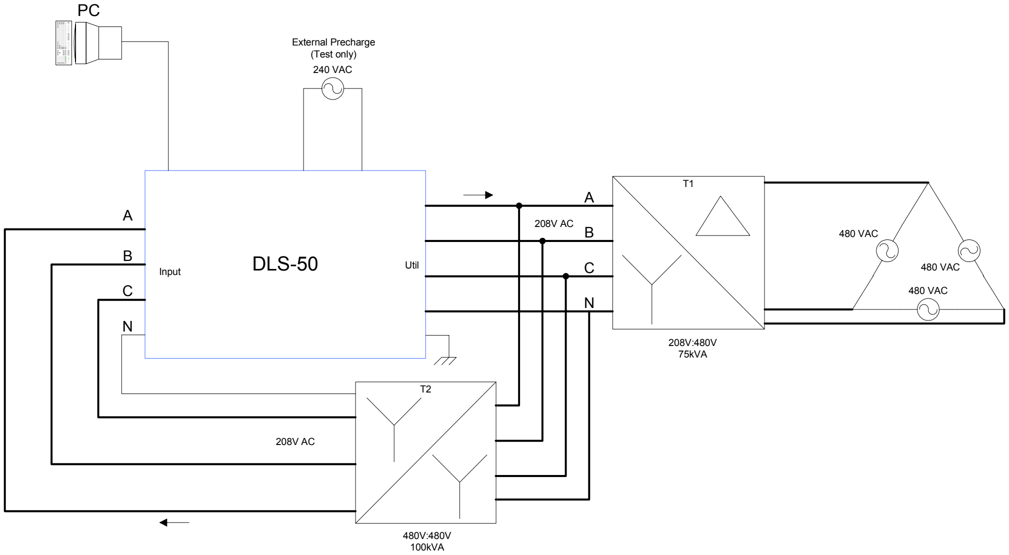


Figure 28 Test Set-up

<u>Normal Tests</u>

The data collection was performed using the utility as the input to the system (as shown in Figure 7). A direct voltage measurement of the input was used for synchronization during testing. It should be noted, that the customer will be using a motor drive (unfiltered inverter) as the input to the system. This difference may affect the system and should be tested.

Parameter verification at 60Hz

The test objective was to verify that the GTL-50 regulated input current at 60 Hz over the full range of loads. It was also important to verify the response to a transient, measure the THD, and measure the temperature while operating at 60 Hz.

Input Side

The operation of the input side is demonstrated by the waveforms in Figure29 and Figure 30. The top waveform is phase A voltage and the bottom three waveforms are phase A, B, and C currents.

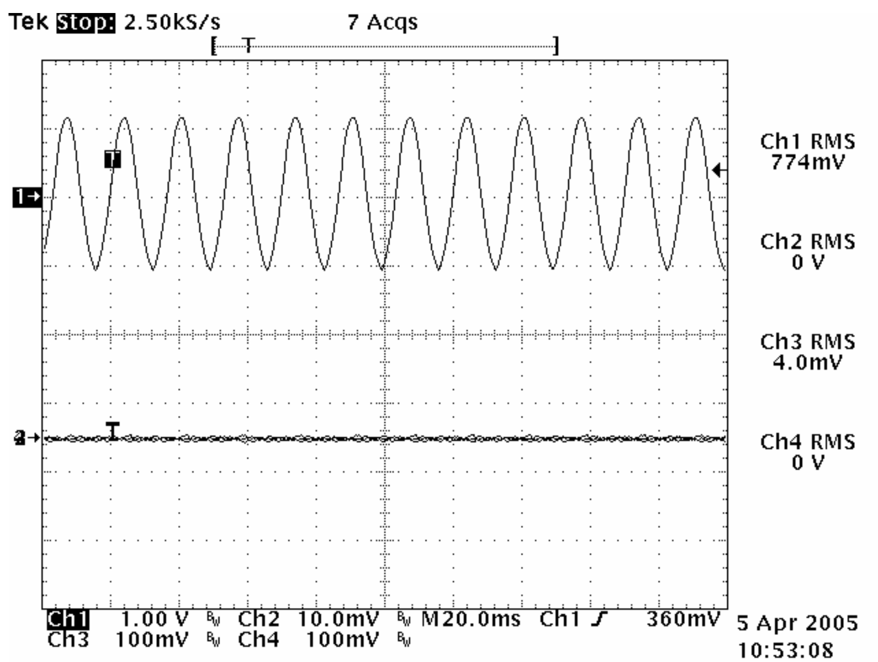


Figure 29. 60 Hz Input Waveforms at No Load

Figure 30 shows the unit operating at rated power (50kVA), or 140 Arms with unity power factor. Figure30 shows a 0.8 power factor at 50 kVA. The M3 waveform is just the inverted voltage so that the power factor was obvious. The current and PF are regulated quite well over the full power range.

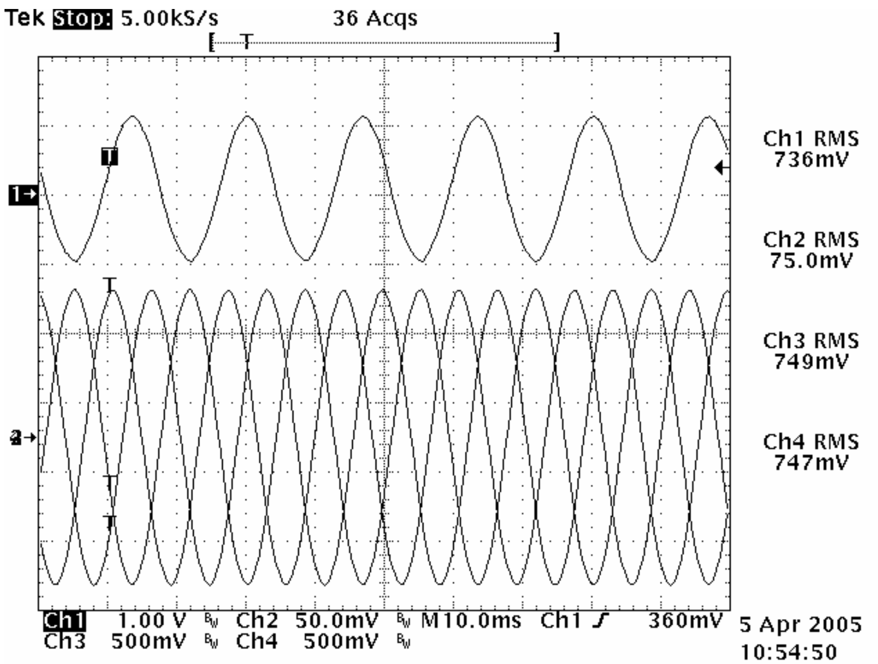


Figure 30. Input Waveforms at 50 kVA, PF = 1

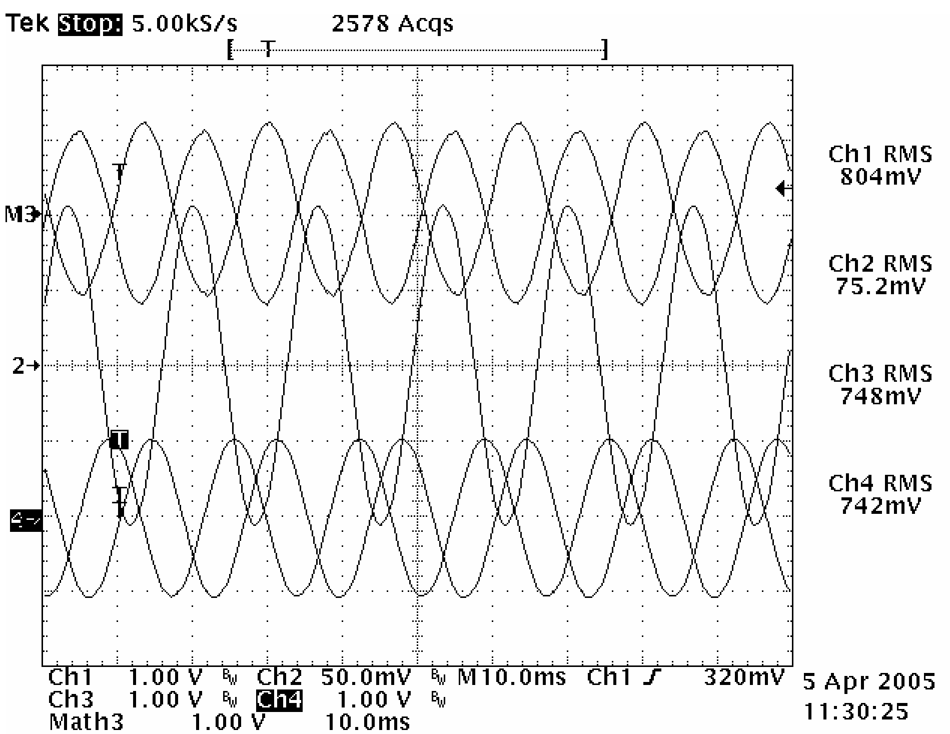


Figure31. Input Waveforms at 50 kVA, PF = 0.8

The transient response is shown in Figure 32, and it can be determined that the input current ramps very fast, without any overshoot.

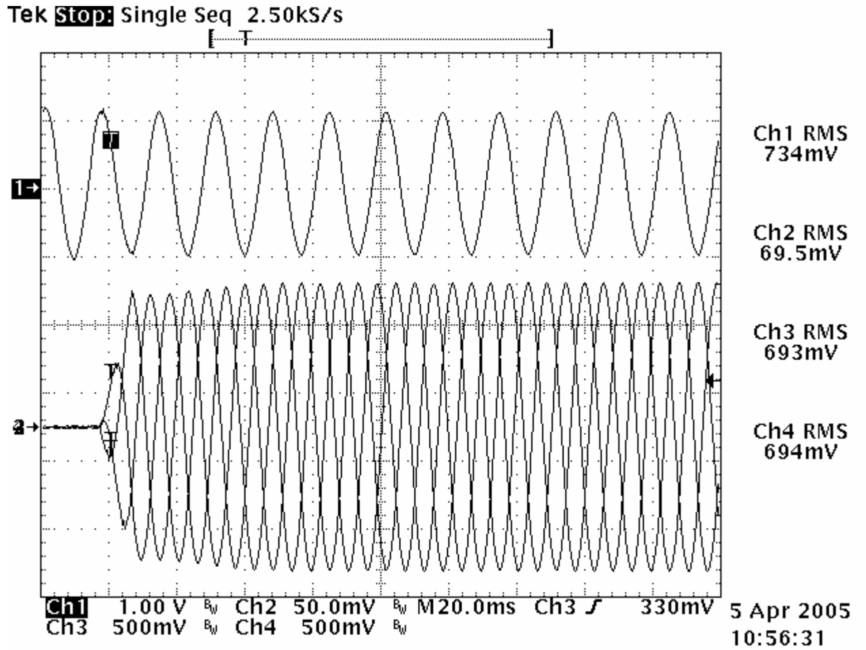


Figure 32. Input Transient Response

Utility Side

The operation of the utility side is verified by the waveforms in Figure 33, where the top waveform is the DC bus voltage (AC coupled) and the bottom waveforms are the currents out of the GTL-50. Figure 32 shows that there is minimal ripple on the DC bus during steady state.

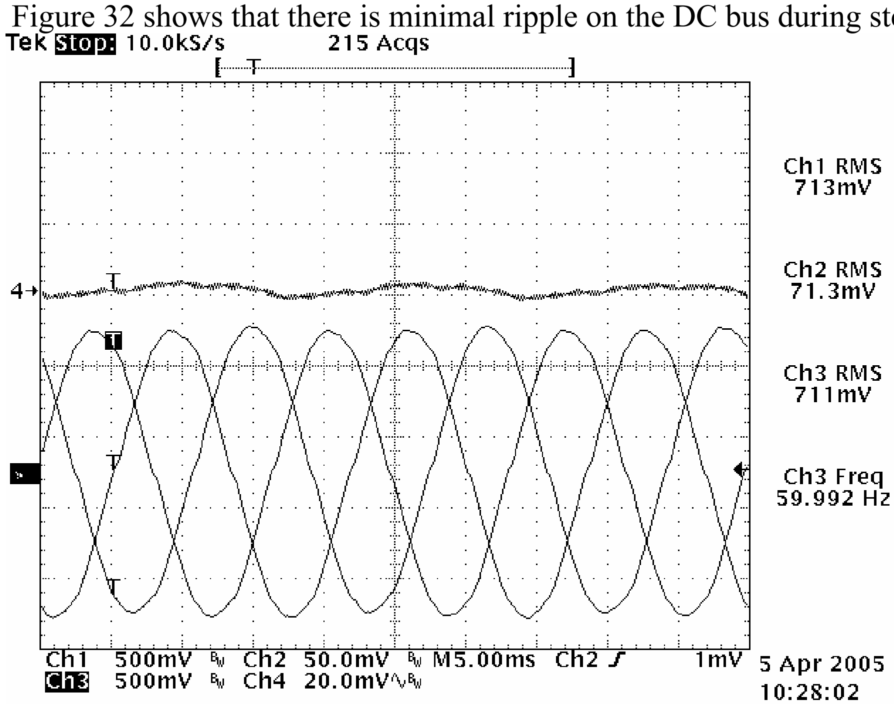


Figure 33. Utility Waveforms at 50 kVA

Figure34 and Figure35 show the dc bus response to a commanded step change from full load to no load and reverse. The bus is currently regulated at 430V.

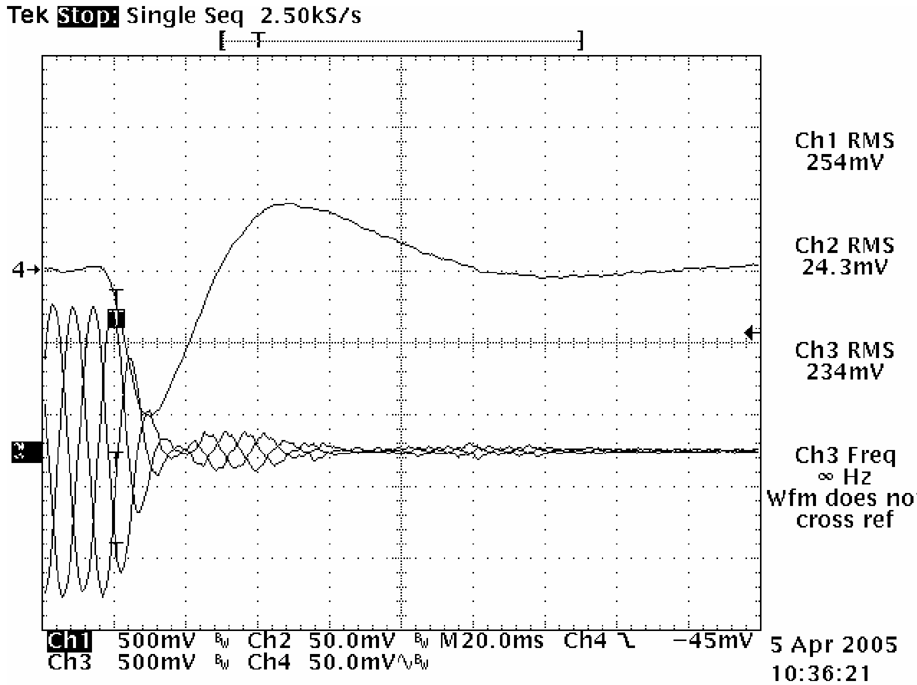


Figure 34. Utility Waveforms during Step from 140A to 1A

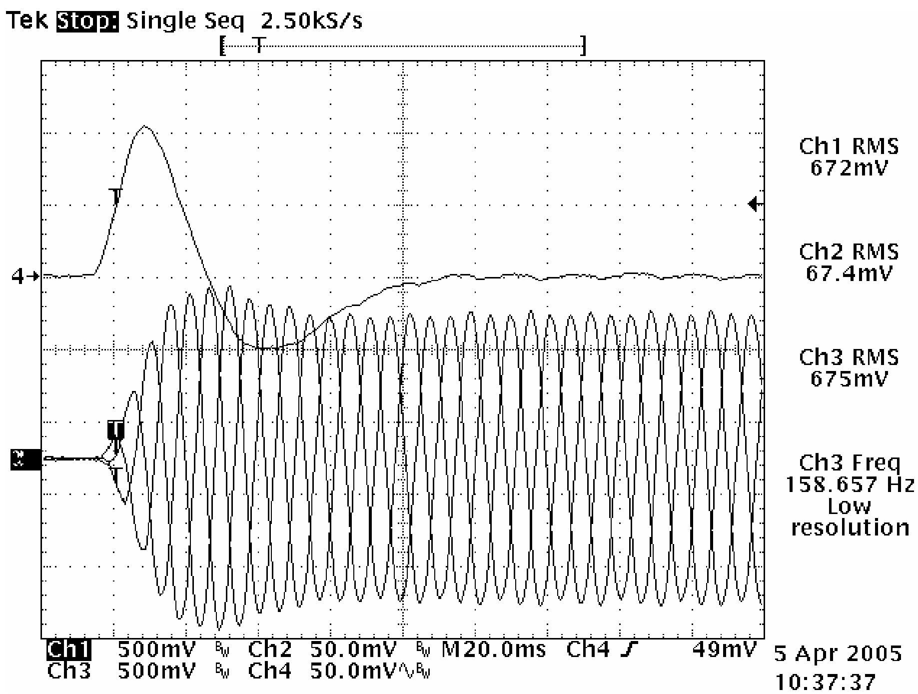


Figure 35. Utility Waveforms during Step from 1A to 140A

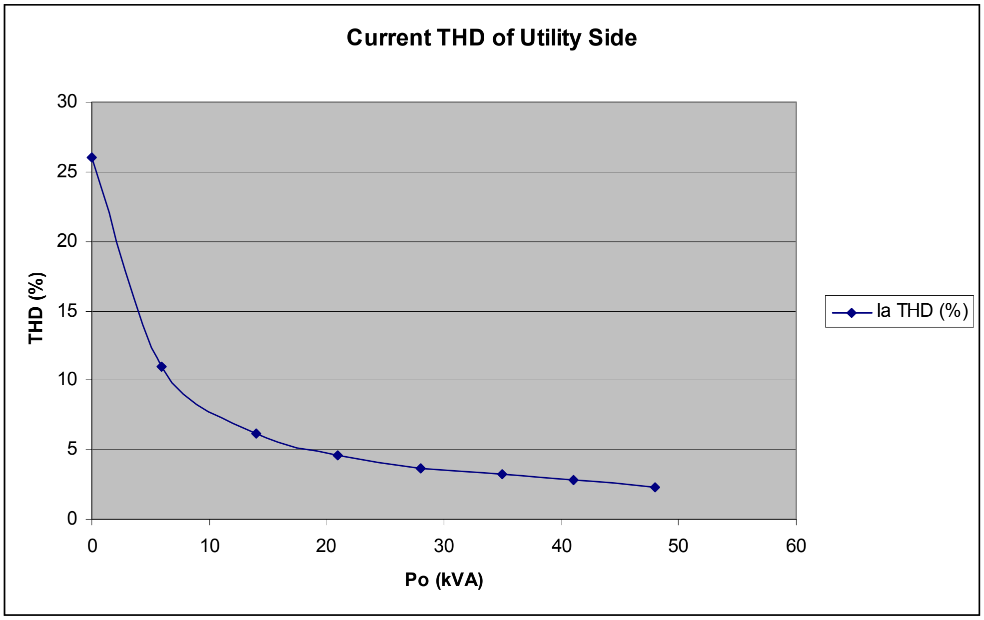


Figure 36. Output Current THD

The current THD is shown in Figure 36 and at rated power the 60 Hz THD is well below 5%. The temperature for several different components is shown in Fig 37. This test was performed at rated power of 50 kW operating at 140A and unity power factor. Although the temperatures did not flatten out (test was stopped due to transformer getting too hot) completely, the steady state temperatures can be estimated. The dip from 2500 to 400 seconds was a shut down of the GTL-50 so that a fan could be added to the external transformer. Overall, the temperatures seem very reasonable and should not be a concern.

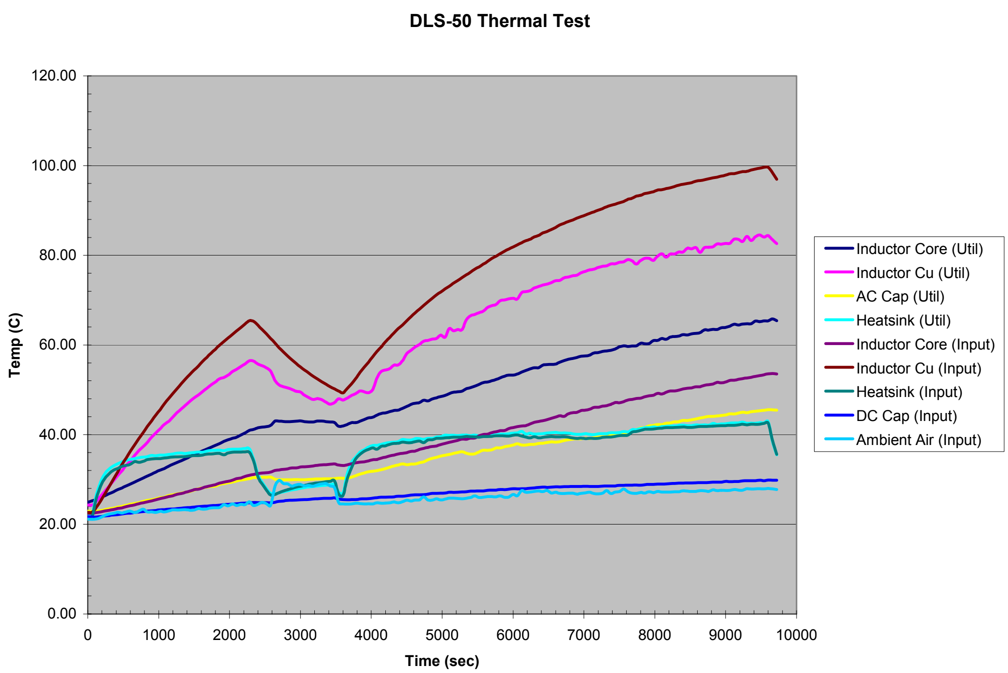


Fig 37 Temperatures during 60Hz tests

Normal Function Tests
EPO switch engaged: Unit turns off safely - *Pass*
Loss of Communication: Unit turns off safely - *Pass*
Remote EPO switch engaged: Unit turns off safely - *Pass*
Removal of input AC connector while unit is ON: Unit turns off safely -*Pass*

Abnormal Tests
Output short circuit: Unit turns off safely – Not tested
Loss of Input Aux supply: Unit turns off safely - *Pass*
Under voltage: Unit turns off safely - *Pass*
Over voltage: Unit turns off safely - *Pass*
Loss of one phase, A then B then C: Unit turns off safely - *Pass*
Loss of Sync: Unit turns off safely - *Pass*
Out of frequency: Simulated
Source, low line: Unit turns off safely - *Pass*
Input Aux supply wrong voltage: Tested by inspection
IGBT short: Simulated
IGBT open: Tested by inspection

Software Verification
The GTL-50 software was tested completely under normal operating conditions. The State Machine was verified and works correctly. The verification was performed by changing states with the LabView interface and checking for the proper system response. The testable fault conditions were verified, and the unit responds correctly in all cases. The fault conditions that were not testable were simulated on a bench and the software responded properly in all cases. CRC checking is performed on all data sent to and from the PC, to make sure that the data is valid. This was verified, because the data was consistently being sent and received.

User Interface
LabView was used as the interface with the operator and the two screens are shown in the figures below. The user can select the current, power factor, and state, and then several system parameters are displayed to indicate proper operation of the system.

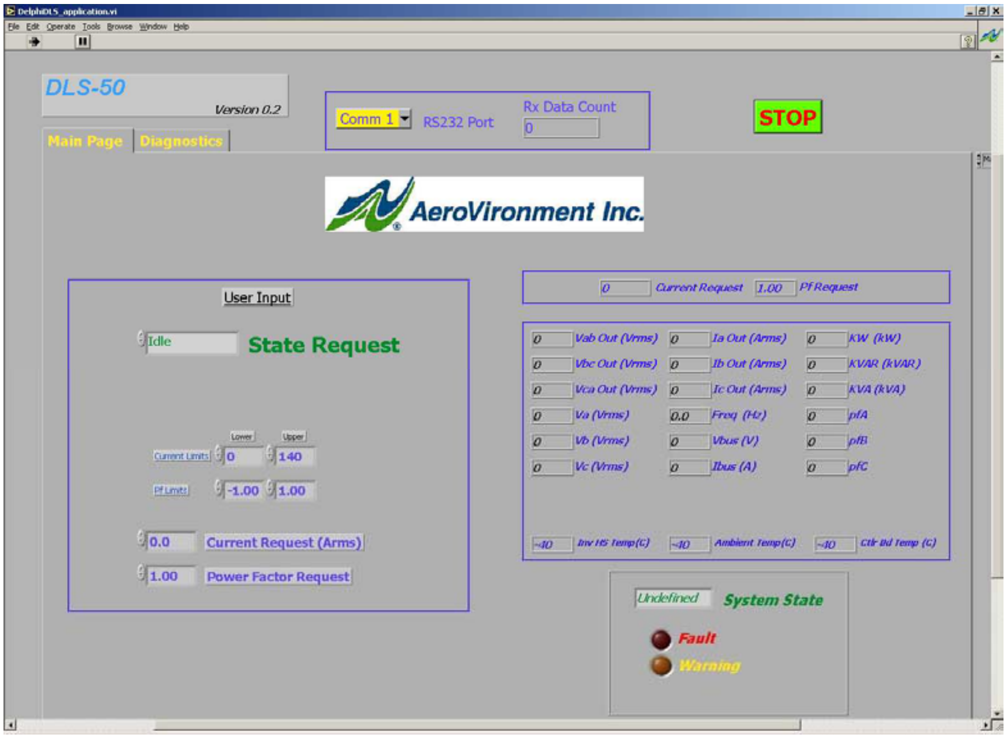


Figure 38. Input LabView Interface

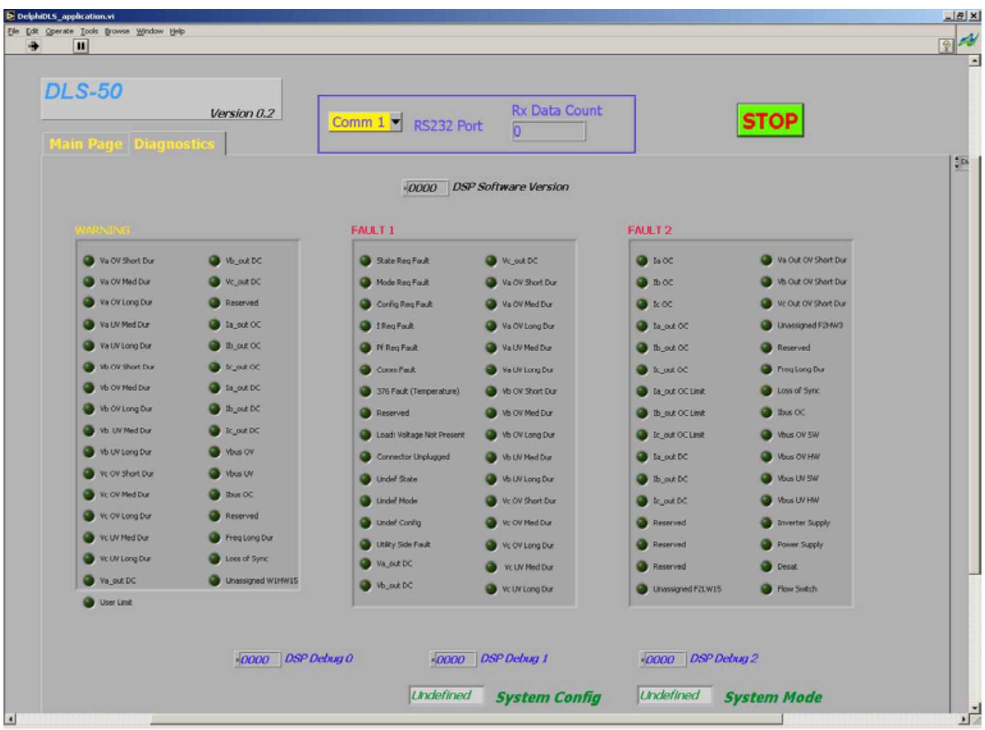


Figure 39. Input LabView Diagnostic Interface

Conclusion

The GTL passed the functional acceptance test. The efficiency of the system at rated power is around 94%.

5. Interphase Transformer (IPT) Technology Development

5.1 IPT Concept

The Interphase Transformer (IPT) technology replaces each semiconductor phase with three sub-phases. Each group of three sub phases is "averaged" using a three-phase interphase transformer. The total semiconductor VA remains unchanged. Digital controls are used to generate precision gate commands for each sub-phase. The IPT topology is shown below.

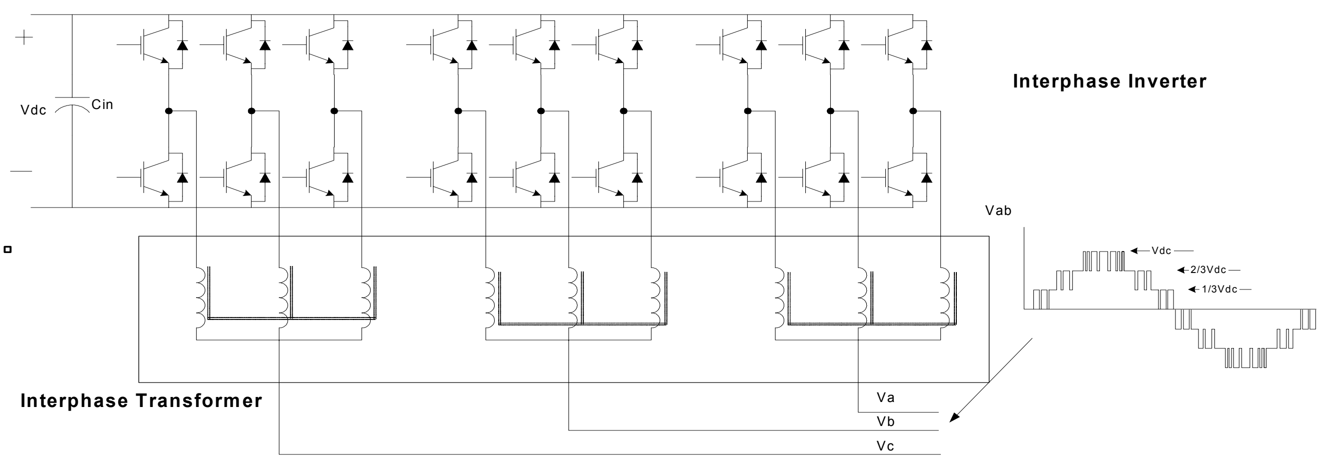


Figure 40. Interphase Inverter Topology

Benefits of the IPT technology include:

1. Switching ripple currents are reduced by approximately a factor of five in rms. This virtually eliminates loss components associated with switching ripple. This in turn means improved efficiency, greater range, and improved battery life.

2. Due to harmonic cancellation, the required size of the DC bus capacitor is reduced by factor more than two. This results in associated cost and size improvements.

3. When used in connection with the bidirectional recharge concept and PWM inverters, the size and cost of the required line filter are each reduced by more than a factor of ten.

A more detailed analysis of AV's interphase transformer design is shown below.

5.2 Interphase Transformer Analysis

Introduction and Background

In both DC and AC power processing applications, voltage and current regulation is achieved by the topology shown in Figure 41.

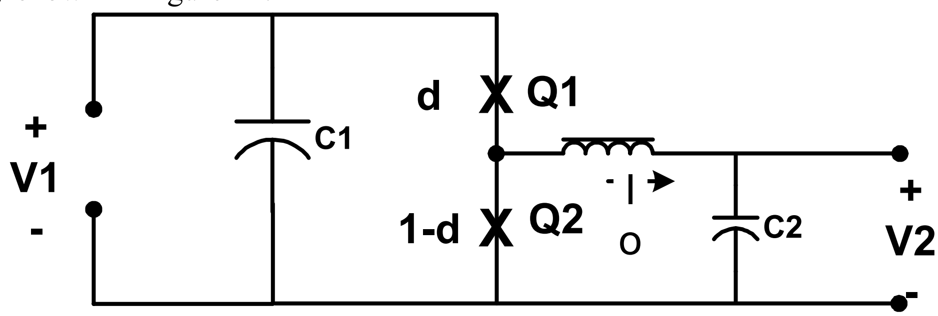


Figure 41. Basic regulating element

While great advances have occurred for the semiconductors used in the Figure 41 scheme, little progress has occurred in connection with the inductor. As such, the inductor remains the largest and most massive component for most applications. In typical applications, the inductor mass ranges between 100 g and 2 kg or more per kW of power handled. A new scheme, based on the use of sub-phases and an interphase transformer is shown in Figure 42. With the new scheme, the total magnetics mass is typically reduced by approximately a factor of three compared with the Figure 41 scheme. Other advantages are also provided such as reduced magnetics loss, reduced ripple current in the DC bus capacitor, reduced EMI, and improved system bandwidth.

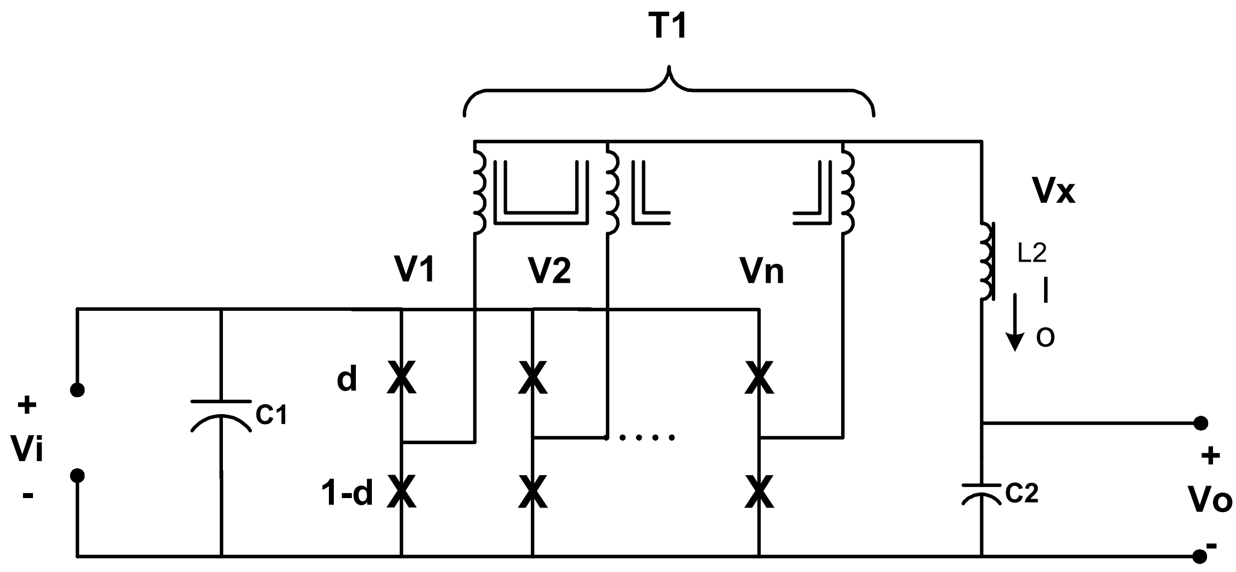


Figure 42. Regulating element using N sub-phases.

For both the Figure 41 and Figure 42 schemes, V_2 and V_1 are related as follows in steady state

$V_2 = D*V_1$, (1)

where V1 is the HV port voltage,
V2 is the LV port voltage,
And D is the switching duty cycle of the high-side semiconductor switch(es).

In the case of the Figure 41 scheme, inductor L_1 functions as an energy storage device. As such, energy is absorbed by L_1 during one part of the switching duty cycle, and released during the subsequent part of the duty cycle. The physical size of L_1 is proportionate to the required energy storage, which in turn is proportionate to the quotient of power and switching frequency.

With the Figure 42 scheme, two processes are involved – transformer action and energy storage. Transformer action, produced by T_1 is such that voltage V_x is equal to the instantaneous average of the individual phase voltages, V_j. In turn, this averaging process greatly reduces the need for energy storage when the individual phase duty cycles are symmetrically spaced. In particular, the energy storage requirement for L_2 falls as $1/N^2$, where N is the number of phases. This means that the size and mass for L_2 is only $1/N^2$ times that of L_1. At the same time, the size and mass of transformer T_1 turns out to be independent of N and only about one fourth the size and mass of inductor L_1. Putting these facts together means that the mass ratio between the Figure 42 magnetics (transformer plus inductor) and the Figure 1 magnetics (inductor) is $0.25 + 1/N^2$. Thus, for a three-phase system, the Figure 42 magnetics mass is only about 36% that of the Figure 41 scheme. Furthermore, since losses are approximately proportionate to mass, it follows that the magnetics losses of the Figure 42 scheme are something like one third those of the Figure 41 scheme.

It is noted that the topology consists of N conventional buck/boost regulators connected in parallel. As such, large circulating currents (current imbalance) will result where only slight differences exist between the respective duty cycles. This issue can be addressed in one of two ways – either by maintaining extremely accurate matches between the individual duty cycles, or by some form of active correction. Both of these options are discussed in Section 5.3.

It is possible to integrate L_2 with T_1 such that a single magnetic element provides both the transformer and energy storage functions. This is discussed in Section 5.3, along with analysis and design equations. Finally, it should be noted that transformer T_1 can be realized by any of several different constructions, including cases where multiple transformers are used.

<u>Analysis of N-Phase Scheme</u>

Voltage at Node V_x

We consider the general case as represented by the Figure 42 scheme. We assume that transformer T_1 consists of N identical windings, each having N_t number of turns as shown on fig 43. From Ampere's law,

$$V_j - V_x = N_t * \Delta\phi_j / \Delta t, \qquad (2)$$

Where $\Delta\phi_j$ is the change in magnetic flux through the jth magnetic branch.

Since the instantaneous sum of the N magnetic fluxes is zero, we can add the N equations represented by (2) to get

$$\Sigma V_j - N^* V_x = 0, \text{ or } V_x = 1/N^* \Sigma V_j \qquad (3)$$

Equation (3) states that the voltage at node V_x is instantaneously equal to the average of the phase voltages.

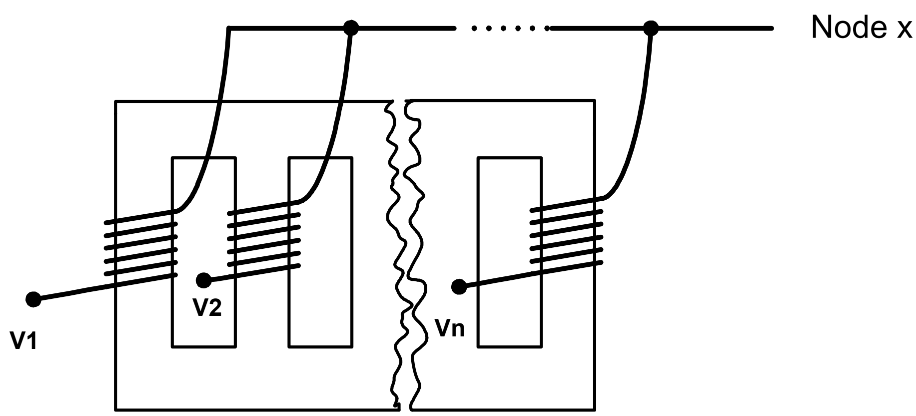


Figure 43. N-Phase-interphase transformer.

<u>Ripple Current through Inductor</u>

In the case where each Vj has duty cycle = D and switches between V = 0 and V = V_b at frequency f_s, and where the individual duty cycles are symmetrically spaced in time, it follows that V_x will be a pulse train of frequency $N*f_s$ and will have a peak-to-peak value of V_b / N. Accordingly, the maximum peak-to-peak current ripple produced when V_x is connected to a voltage source through an inductance of L is given by

$$\Delta I = V_b / (4*N^{2*}L*f_s) \qquad (4)$$

This value of ripple current occurs when D = (2*m -1) / 2*N, where m is an integer (N = 1, 2, …N). Thus, in the case of a three phase system (N = 3), worst-case current ripple occurs when D = 0.16, 0.50, and 0.83. For all other values of D, lower values of ripple current occur. When D = m / N, the ripple current is zero. Note that the effect of the interphase transformer is to reduce the required energy storage by a factor of $1/N^2$, thus enabling L_2 to be reduced by the same factor.

Since the ripple current is triangular, the rms AC current, I_{AC} is given by

$$I_{AC} = \Delta I / (2*\sqrt{3}) = 0.289*\Delta I \qquad (5)$$

Each of the N sub-phase currents is mutually equal and hence each is equal (instantaneously) to 1/N times the instantaneous current through L_2.

Required Magnetic Cross Section

There are two issues which determine core size – magnetic saturation and core heating. In general, core size will be determined by only one of these two factors. The total core heat dissipation, Pc, is given by

$$P_c = K_c*B^{2+\alpha} * f^{2-\beta} *V_c, \qquad (6)$$

Where K_c ,α, and β are material constants, and V_c is the core volume. For a given core design, the surface cooling area, A_c, is proportionate to V_c raised to the 2/3 power. Hence,

$$A_c = K_a* V_c^{2/3}, \qquad (7)$$

where K_a is a proportionality constant based on core shape. Heat flux, H, at the cooling surface is equal to P_c / A_c. Hence,

$$H = (K_c / K_a)*B^{2+\alpha} * f^{2-\beta} *V_c \qquad (8)$$

Equation (8) determines the maximum value of B based on thermal issues; H must not exceed a critical value. Hence,

$$B_o \leq [H_o*K_a*B^{-(2+\alpha)}f^{(2-\beta)}V^{-1/3}]^{1/(2+\alpha)}, \qquad (9)$$

where H_o is the maximum allowed heat flux and B_o is the flux density which results in H_o. B_o must also be less than B_m, the saturation flux density of the core material. This requires that the minimal core cross section, A_c, associated with each winding be given by

$$A_c = V_b / (8*N_t*f_s*B_o), \qquad (10)$$

where V_b is the maximum voltage on the HV port, N_t is the number of turns, f_s is the switching frequency, and B_o is the maximum allowed flux density.

For optimal efficiency, the winding loss should approximately equal the core loss.

Core Material and Optimal Switching Frequency

For most applications, Ferrite core material is optimal. Because of the relatively low loss characteristics of these materials, transformers using Ferrite cores potentially provide the highest power densities and at the lowest costs – provided moderate to high switching frequencies are used. While other core materials offer higher saturation flux densities, this is of benefit mainly where the switching frequency is constrained to a relatively low value. Optimal switching frequencies vary approximately with the reciprocal square root of the through power. At 100 kW, the optimal switching frequency (using IGBT's) is approximately 15 kHz and at the 100 W level, the optimal switching frequency is on the order of 400 kHz (using MOSFETs).

In conventional single phase switching applications, Ferrite cores are generally not optimal for energy storing inductors due to the relatively small flux swing. In these applications, other core materials, such as powder cores work better because of the larger flux swing afforded by the higher core saturation. In the case of the interphase transformer, the flux swing is nearly symmetric (between – Bm and +Bm); this allows Ferrite materials to be fully utilized.

Optimized Design

Figure 44 depicts a core design suitable for a three-sub-phase scheme. Dimensional ratios have been selected such that the transformer specific power is maximized where surface heat flow is assumed constant.

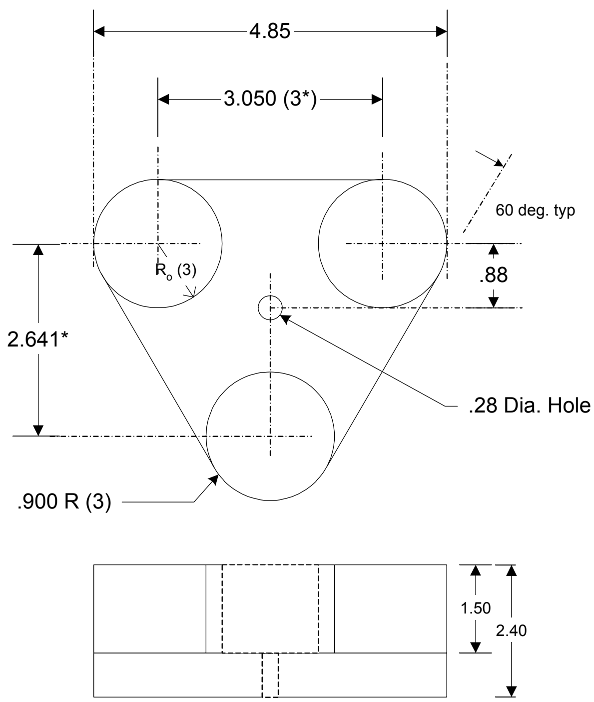


Figure 44. Transformer design for the Figure 42 scheme

Alternative Topologies and Transformer Designs

Various transformer topologies may be used in place of the one shown in Figure 2 and core designs may be employed, which are alternative to the Figure 44 design.

Two-Phase Schemes

Where two sub-phases are involved, the Figure 42 scheme may be replaced by the topology shown in Figure 45, where T_1 consists of a single winding having a center tap.

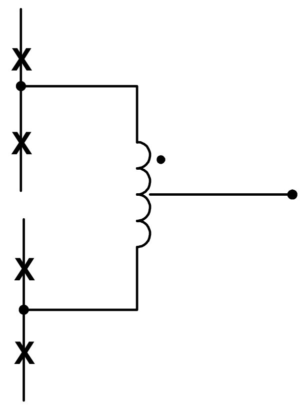


Figure 45. Two-phase topology

The construction of T_1 may use a conventional shell-type (e.g., E-E, E-I, or pot type) core where both halves of the winding are applied to the center prong. The two winding halves may be concentric or bifilar-wound. The concentric winding has moderate leakage inductance and thereby can provide part or all of the required L_2 inductance – providing the advantage that the inductor can either be eliminated or reduced in size. There are, however, three negatives to the concentric winding approach which must be addressed. The first issue is that some of the leakage flux enters the core and can cause localized saturation when currents are high. This problem can be compensated by increasing the core size. Next is that the leakage flux enters the winding and causes eddy losses. This problem may be handled in one of two ways – either by maintaining a low ripple factor, or by using a special winding conductor such as Litz wire. If inductance L_2 is provided via leakage only, then a relatively high value of leakage must be provided such that the ripple current is maintained at a low value; this means increased core saturation issues. If an external inductor is used, then the size of this inductor must be larger than would otherwise be required. Finally, the stray B field may also be of concern in some applications. In summary, the concentric winding has the advantage of enabling the elimination of the external inductor – provided the core and winding is designed to deal with the leakage flux.

If a bifilar winding is used, leakage flux is very low. This means that core saturation and winding eddy loss problems are minimized and in most cases, foil windings can be used without eddy loss concerns, even where ripple currents are relatively high. Furthermore, the foil winding is usually low cost and has a high packing factor, thus enabling the transformer size to be minimized. The one negative is that an external inductor must be used.

For both the concentric and bifilar windings, the usual options are available: round, square, or rectangular copper magnet wire, copper foil, and aluminum foil. For each of these, various types of insulation systems are available.

For the two-prong construction, leakage inductance is higher than for any of the other constructions, assuming each winding half is applied to an individual prong. In cases where current densities are low, this has the advantage of high leakage inductance. In most cases, the leakage flux entering the winding is such that foil windings cannot be used due to excessive eddy losses. However, with two prong core designs, portions of each winding half may be applied to each prong such that leakage fluxes are reduced. In the extreme, full bifilar windings can be applied such that leakage flux levels are negligible. Again, when this is done, an external inductor is required for L_2

Binary Phase Schemes

The scheme on fig 45 can be extended to include increased numbers of sub-phases, provided that only binary numbers of sub-phases are involved. Figure 46 depicts the next step where four sub-phase are used.

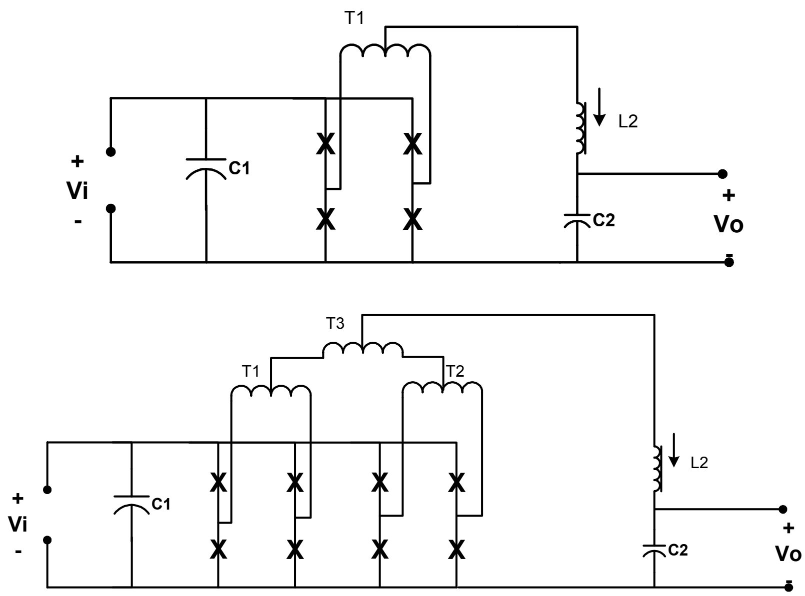


Figure 46. Four-phase binary topology

This approach can obviously be generalized to 2^N sub-phases. While these schemes benefit form the fact that similar transformers can be used, they suffer from reduced transformer utilization. This is seen, for example, in the Figure 6 four-phase scheme. Here, no AC voltage is across T_3 when the switching duty cycle is 50%. At this point, T_3 provides no benefit. This is in contrast with the original Figure 2 scheme where all portions of T_1 are equally used.

Ring Balance Scheme

Figure 47 depicts a topology where T_1 of the Figure 42 is replaced with N transformers, each having two windings. With this scheme, the jth transformer serves to balance the jth phase current with the (j+1)th phase current; the Nth transformer serves to balance the Nth phase current with the first phase current. The end result of this scheme is the same as the Figure 42 scheme – a summing node is established (V_x), the voltage of which is equal to the average of the individual sub-phase voltages (V_j). The advantage of the Figure 47 scheme is that any number of sub-phases can be handled, using conventional two-winding transformers. Transformer utilization is inferior to that of the Figure 42 design, but superior to that binary phase systems.

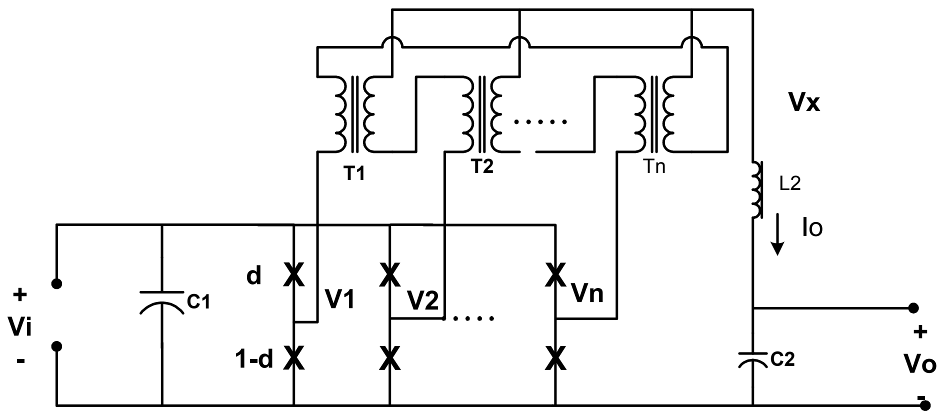


Figure 47. Ring Balance Scheme

Based on symmetry considerations, it can be shown that the voltage, E1 on either winding of T1 is given by

$$E_1 = (1/2N)*\Sigma(N+1-2j)*V_j, \qquad (11)$$

where the summation is for j = 1 to N. Similar expressions are obtained for the other N-1 transformer voltages.

<u>Integrating the Transformer and Inductance Functions</u>

For the Figure 42 scheme and for any of the alternative schemes, L_2 can be replaced by taking advantage of leakage inductance within T_1 provided attention is paid the following:

1. Selection of core with appropriate dimensional ratios.
2. Design of core and winding such that localized core saturation is prevented under worst case conditions.
3. Design of winding such that eddy losses within winding are maintained adequately low.

For a three-phase core having the generic dimensions shown in Figure 48, the Leakage inductance, L_s, is given approximately by

$$L_s = 1.26*N_t^2*R*(1.73*A^2 + 6*A - 6.28) / B, \qquad (12)$$

where Ls is in uH, N_t is the number of turns applied to each core prong, R is the radius of each prong in meters, and A and B are aspect ratios which are defined in Figure 8.

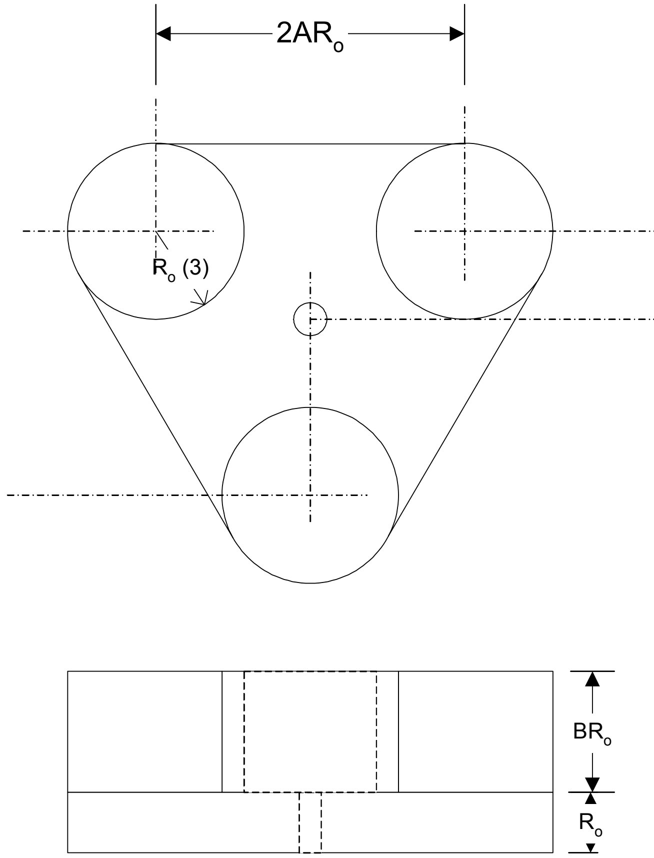


Figure 48. Generic Three-Phase Transformer Core (two identical halves are used)

Note: Dimensionless constants A and B are selected to provide desired leakage inductance and to achieve some other criteria such as minimized loss.

In the case of a three-phase core having dimensions equal to those shown in Figure 44, and where 17 turns are applied to each of the three prongs, Equation (12) predicts an inductance of 22 uH. (The measured inductance for a transformer of this exact construction was 19 uH.)

Equations (4) provides a measure of the maximum peak to peak ripple current as a function of bus voltage (V_b), switching frequency (f_s), and leakage inductance (L_s). In the case where Vb = 600 V, fs = 15 kHz, and Ls = 19 uH, the peak-to-peak ripple current predicted by Equation (4) is 58.5 A. (The measured ripple current was 61 A.)

Leakage inductance can be controlled by adjusting the values of A and B. As A/B is increased, leakage inductance increases. High values of leakage inductance are desired in that they eliminate the need for external inductance and provide reduced ripple currents. In turn, as ripple currents fall, the associated AC losses quickly fall (due to the squared dependence). In many situations, this enables the use of foil or strap windings (which have relatively high AC resistance values), as opposed to a Litz type winding. In addition to reduced cost, foil windings have the added advantages of high packing factors and efficient heat transfer. However, for large values of A/B, it appears that “premature core saturation” can occur where leakage flux enters the core and adds to the “magnetizing flux component”. Thus far, no analysis has been carried out to determine optimal values for A and B. However, experimental results indicate that adequate per unit inductance is achieved for a three phase core where A is approximately 1.7, B is approximately 3.5, and the core cross section, Ac, is increased to 1.15 times the value listed in Equation (10).

In general, it appears that using leakage inductance in place of an external inductor makes sense as cost, mass, and losses are all reduced. Furthermore, observing that the required leakage inductance goes as $1/N^2$, it follows that lower values of A and higher values of B become acceptable where four or more sub-phases are used.

5.3 Detailed Developmental Tasks

Topology selection

The interphase transformer scheme in a generic technique, which can be used in both AC and DC environments to reduce cost, losses and mass associated with filter inductors. This part of DOE program started with extensive evaluation of the best demonstration environment in terms of the wider use applications, meaningful harmonic suppression, power range, benefit for the other projects, number of phases, type of switches and cooling media. According to the original program plan the ITP technology was supposed to be verified based on a three-phase 75kW DC-AC inverter (total of 9 sub-phases and 18 gate drives) using conventional IGBT power switches (air cooled) operating at 400VDC bus voltage.

The other major task was the assessment of our current DSP controller capability to control 9 sub-phase IPT demonstrations. After extended evaluations including component level testing we concluded that our present controller does not have the capability to control 9 sub-phases due the PWM shifting limitations.

Based on extensive evaluation of the IPT topology and hardware/software requirements, revisions to the original plan have been made. We decided to use a 150 kW iPower PEM (Power Electronic Module) based on Alpha technology for both the power stage and controls for the testing and evaluation. We made the decision to test a single node of the IPT filter concept using a custom designed three-sub-phase transformer plus filter capacitor. This approach allows us to validate the IPT filter concept without implementing a complete nine-sub phase IPT based inverter system. The iPower hardware is viewed as a test instrument, while the single three-sub-phase IPT and filter capacitor are viewed as the hardware under test (HUT). The HUT will be evaluated for weight, size, power loss, temperature rise, filter effectiveness, transfer function, dynamics, and magnetic saturation limits.

The advantages of this new approach include the following:

- The main development effort focused on validating and proving the Inter Phase Transformer concept
- Reduced effort and time in connection with the support power electronics

- Use of Alpha hardware in connection with the demonstration
- Direct comparison between conventional filter techniques and interphase filter techniques.
- Demonstration of interphase filtering at the 150 kW level

<u>IPT Design and Fabrication</u>

After selecting the testing medium the IPT design process was started. Based on the inverter rating the design of 150kW ferrite cores and windings for the interphase transformers was completed. The new IPT filter was designed to meet the original iPower filtering specifications including leakage inductance and output capacitance thus allowing for direct comparison with conventional inductor filter technology. The vendor, Ceramic Magnetics Inc., for the custom ferrite IPT cores was selected. The main components: core and custom Litz wire were procured. The vendor claiming the manufacturing equipment problem delayed the IPT delivery for one month. After receiving the core material from Ceramic Magnetic, the winding process with Litz wire took place in our facility. The first IPT unit successfully passed the bench level component test and was ready for the final assembly with the AC capacitor filter. The whole transformer-filter assembly was ready to be integrated with power stage test fixture. The second replacement IPT unit was also procured.

<u>IPT Software development</u>

Another major task completed was the selection and verification of the DSP control platform capable of successfully completing all the ITP development. The reduction of the sub-phases from nine to three, as explained in above section allows to use our off the shelf DSP controller. Significant time was spent coding and bench testing CPLD algorithms for PWM generation, dead time and fault management.

The major task completed in August was the development of new DSP algorithms to evaluate the IPT concept. The algorithms are based on the detailed IPT test plan and procedures and are operating our internally develop DSP based hardware platform. The new ITP algorithms were simulated and verified during the bench test and are ready for system integration with the IPT hardware.

<u>Test fixture setup and test plan</u>

Another major task completed was the development of a detailed test plan and procedures for IPT verification testing. Based on this test procedure the modifications to the existing DSP software were made to prove the IPT technology. The other major task completed was modification of the power electronics fixture, which is necessary for IPT testing. The new DSP controller was assembled and passed all functional tests. The IPT software with new algorithms was loaded and the DSP controller and iPower test fixture was ready for final IPT verification tests.

Per our test plan, the verification tests were divided into three groups:

- Parametric Tests
- DC Type Tests (constant duty cycle)
- AC Type Tests (modulated duty cycle)

The purpose of the Parametric Tests was to directly measure transformer parameters under non-operating conditions.

For the DC Type Tests, the ITP-Filter Capacitor assembly was connected to the iPower test fixture with the filter output connected to an ABC-150, which serves as a load by operating in the differential current sinking mode.

For the AC Type Tests, the ITP-Filter Capacitor assembly was also connected to the iPower test fixture with the filter output connected to an adjustable resistive load capable of handling current up to 225 A rms with power dissipation up to 50 kW.

IPT verification testing

The verification testing phase of the IPT development started by conducting the parametric tests, where the transformer-filter parameters were measured under non-operating conditions. Parameters included:

- DC winding resistance
- Core saturation volt-seconds
- Leakage inductance
- Winding-to-ambient thermal impedance

Next, the transformer-filter was integrated with the power stage test fixture and the initial startup tests took place. A significant amount of time was spent to modify and validate the DSP algorithms for the current balancing scheme. The tests started at very low current and voltage levels and progressed to the performance goal of 800VDC and 225Amps.

Both DC Type Tests (constant duty cycle) and AC Type Tests (modulated duty cycle) were conducted. In the beginning, under AC conditions (where the PWM is modulated), we observed the onset of magnetic saturation between 600 VDC and 700 VDC bus voltages. The initial assumption was that the magnetic saturation was due to leakage flux entering specific regions of the Ferrite core. More careful observation, however, indicated that the current balance scheme was not working as expected. After changing one of the current balance control parameters, operation at the higher bus voltages was achieved without saturation.

Next, IPT tests were conducted at with bus voltages up to 800 VDC. The goal was to determine the envelope where magnetic saturation occurs and to compare these results with the predictions provided by the design equations.

While operating at 800VDC bus voltage the IPT envelope of magnetic saturation was determined and compared with the predictions provided by the design equations.

All the all tests described in the IPT test plan were successfully completed and the results met the design objective proving the IPT concept.

The last task added to the IPT scope was to compare the performance of the IPT with cooper foil versus Litz wire. The IPT with copper foil offered higher packing factor and overall lower manufacturing cost.

The results show that for 60 deg C winding temp rise (600 V bus and 50% duty cycle) the current rating for Litz winding IPT is 65 A. Under the same conditions, the foil winding rated current is 91 A. Furthermore, by increasing the leakage inductance just a little, the eddy loss component can be significantly reduced (because of the I squared dependence). The conclusion was that the IPT with foil winding is better due to the higher current rating, lower cost and higher packing factor.

5.4 IPT Test Results

Test Set-Up

IPT tests were structured and performed to evaluate the following:

- To confirm that core saturation can be prevented by using an identified control algorithm
- To compare transformer losses with those predicted analytically
- To demonstrate that the required inductance can be achieved as leakage inductance within the interphase transformer itself
- To demonstrate that core saturation does not take place in a case where the duty cycle is modulated to provide AC

To answer these and other questions, an experimental set-up was devised that used three switching poles (termed sub-poles), a three-phase interphase transformer, and a digital controller (see Figures 49 and 50). Together, these components performed the function of a "filtered power pole". Power input was provided by a DC power supply capable of supplying voltages up to 900 VDC with currents up to 250 A. A 100 kW adjustable load can be connected for either of two modes of operation.

Each of the three sub-poles is rated for 900 VDC (input port voltage) and 300 A rms continuous (output port current). The phase output of each sub-pole is current sensed. The digital controller to maintain duty cycles such that transformer saturation does not occur uses these current sense signals.

With the first mode, the resistive load connects between the pole output and the negative bus. In this mode, the voltage applied to the load is equal to the input voltage times the switching duty cycle, D. This mode is used to test the interphase transformer system in a "DC environment".

With the second mode, the resistive load connects between the pole output and capacitors, which connect to the positive and negative buses. In this mode, DC voltage is blocked from the load resistance. By modulating the duty cycle, an AV voltage component can be generated which in turn enables an AC current to flow through the load. This mode is used to test the interphase transformer system in an "AC environment".

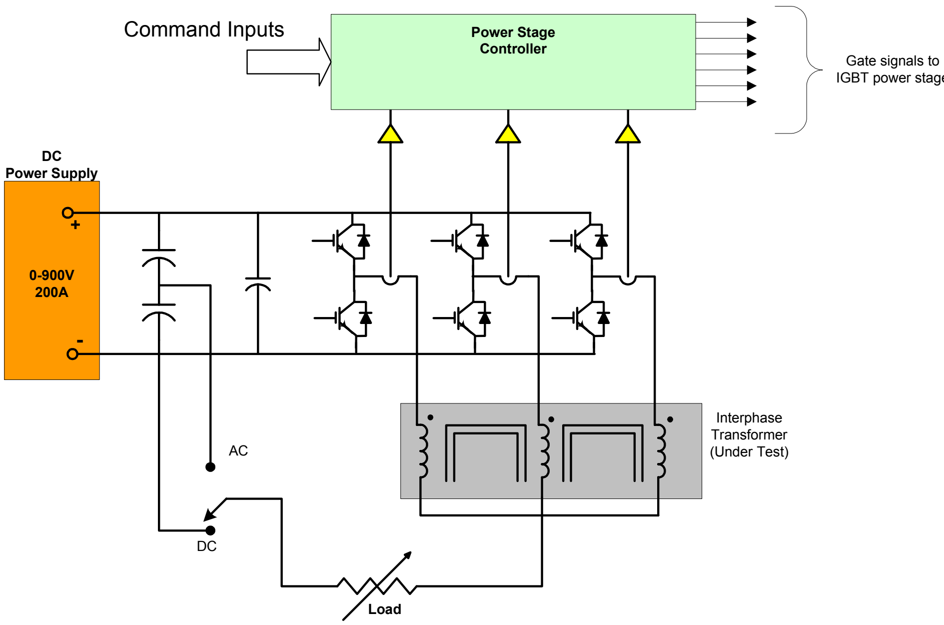


Figure 49. Test Set-Up for Interphase Transformer Scheme

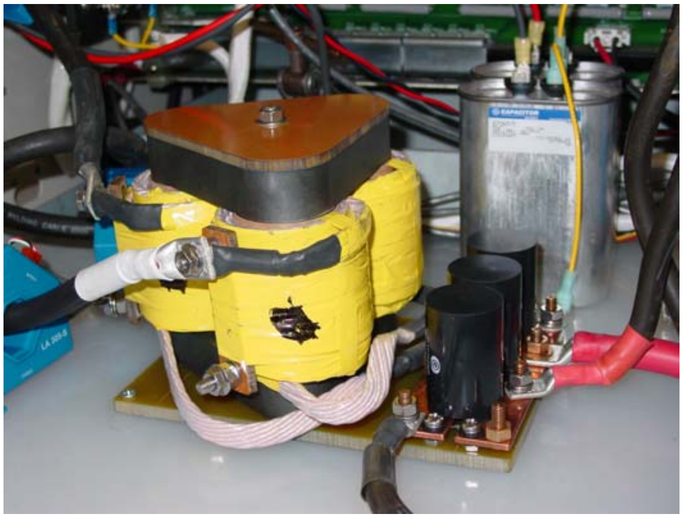


Figure 50. Photograph of Test Set-Up

Transformer Design

The following ratings were arbitrarily set for the complete power pole:

1. Maximum DC bus voltage: 900 VDC
2. Maximum output current: 300 A RMS
3. Switching frequency: 15 kHz
4. Maximum hot-spot temp rise 40 C
5. Per unit leakage inductance 6%

In turn, these four parameters served as inputs for the design of the three-phase interphase transformer. Ferrite material was selected for two reasons:

Ferrite losses at 15 kHz are low relative to other core materials.
Ferrite can be molded into custom shapes. (The configuration of Figure 48 was selected as this provides minimal mass and minimal losses.)

Using Equations (6) through (10) and (12), core dimensions and winding parameters were established. These include:

1. Prong diameter: 1.800”
2. Prong center to center: 3.050”
3. Prong length: 3.00”
4. Core baseplate thickness: 0.900”
5. Winding (each of three): 17 turns of #4 Compacted Litz

Figure 51. Photograph of Three-Phase Interphase Transformer

IPT Test Data - Measured Transformer Parameters

One transformer was fabricated in accordance with the above design and parameters. Winding resistance, leakage inductance, and saturation volt-seconds were initially measured at low power using laboratory instruments. The volt-seconds required for saturation were measured by applying a variable voltage 60 Hz sinewave and observing the current waveform (for indications of saturation). Measured and predicted values are listed in Table 17.

Table 17. Predicted and Measured Transformer Parameters

Parameter	Predicted Value	Measured Value (average of three)
Winding Resistance (Ohm)	0.0045	0.0051 (0.0015*)
Leakage Inductance (uH)	15.5	19.2
Winding volt-sec @ saturation	0.020	0.024
Total Transformer Mass (kg)	---	4.87 (7.1*)

* Values associated with foil wound version of transformer

DC Mode Tests Data

Tests were run using the Figure 9 test set-up set connected for DC mode operation; scope data for these tests is shown in Figures 13 and 14. With the DC bus voltage at 700 VDC, the duty cycle set at 50%, and the output current at 200 A, the measured steady state temperature rise of the windings was 56 C (free convection cooling only).

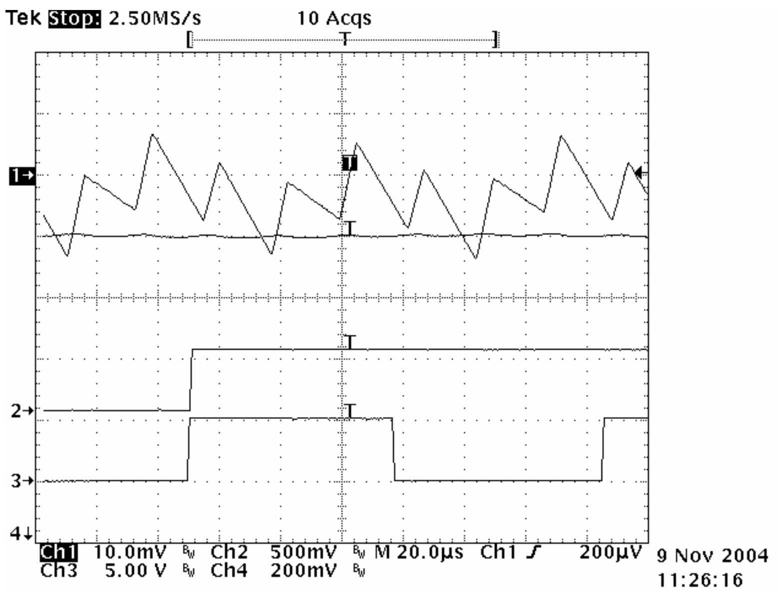


Figure 52 DC test waveforms

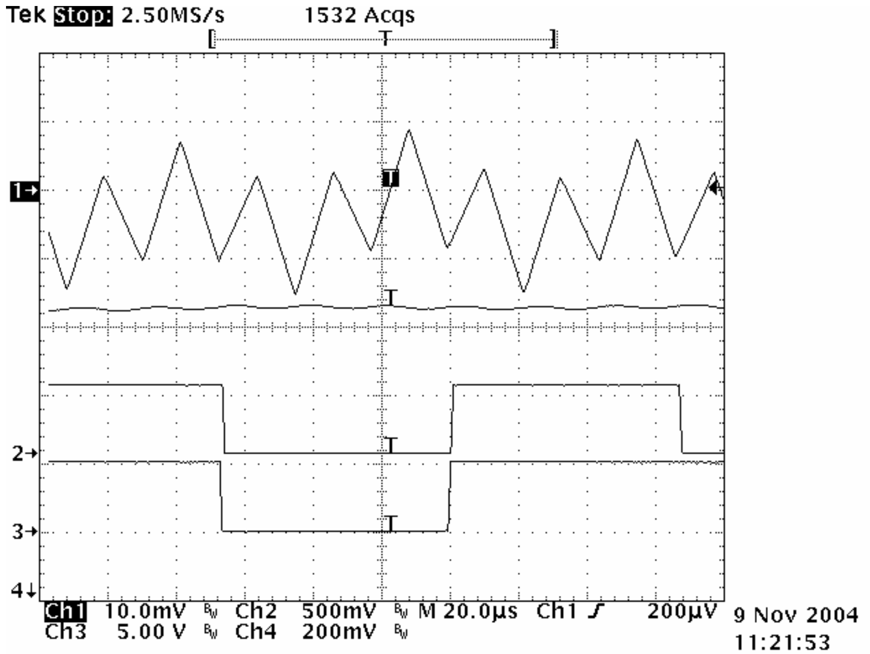


Figure 53 DC test waveforms

The test interphase transformer was constructed with Litz wire to minimize AC losses due to ripple currents. Several design issues should be noted:

1. The magnitude of the ripple current is inverse with the leakage inductance and varies with the duty cycle. The ripple current is virtually independent of the DC or load current
2. The AC loss is equal to the AC resistance times the square of the ripple current
3. For a Litz winding, the AC resistance can be very nearly equal to the DC resistance
4. For a foil winding, the AC resistance is typically many times the DC resistance
5. The packing factor for a Litz winding is typically less than half that of a foil winding

Based on the above issues, it appears likely that foil windings can outperform Litz windings, provided adequate leakage inductance is provided.

A set of three foil windings were made that had similar dimensions to the original Litz windings. The measured resistance for the foil windings was only 30% that of the Litz windings (15 mOhm versus 51 mOhm). Accordingly, the DC losses for foil windings were reduced by more than a factor of three. The measured AC losses for the foil winding were about 2.6 times that of the Litz winding. (With 600 VDC bus voltage and the duty cycle held at 50%, losses within each Litz winding were approximately 2.7 W. Under the same conditions, losses within each foil winding were about 7 W).

With the Litz winding, the maximum continuous output current for the transformer is about 200 A, for a winding temperature rise of 60 C. With air flow, increased current can be handled. With the present foil winding, the predicted rated current is 325 A (free convection). Clearly, the only advantage for the Litz winding is that the no-load losses are less.

AC Mode Tests Results

Tests were run using the Figure 49 test set-up set connected for AC mode operation; scope data for these tests is shown in Figures 54 and 55. No "dynamic problems" were noted for AC mode operation and it is concluded that the closed loop approach works for both DC and AC applications.

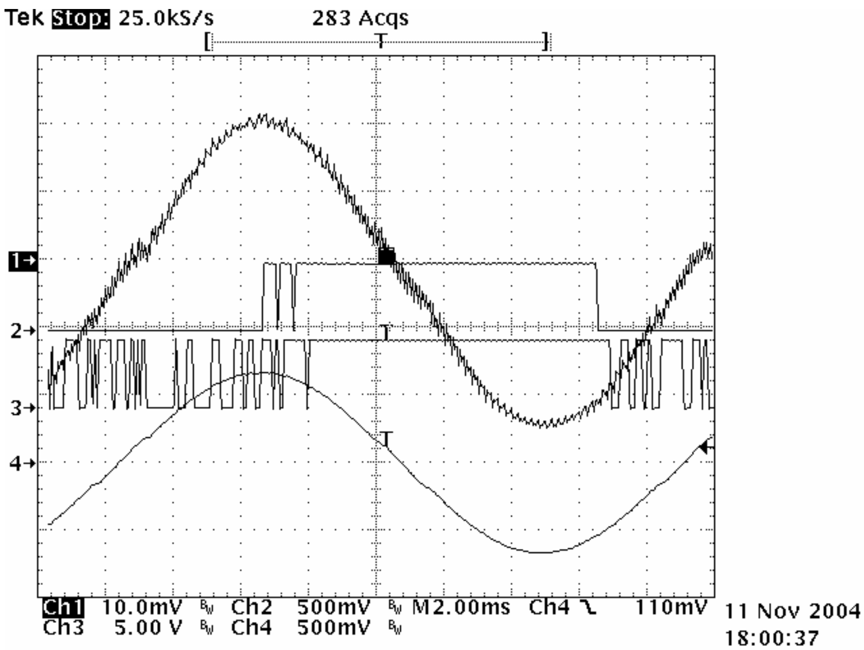


Figure 54 AC test waveforms

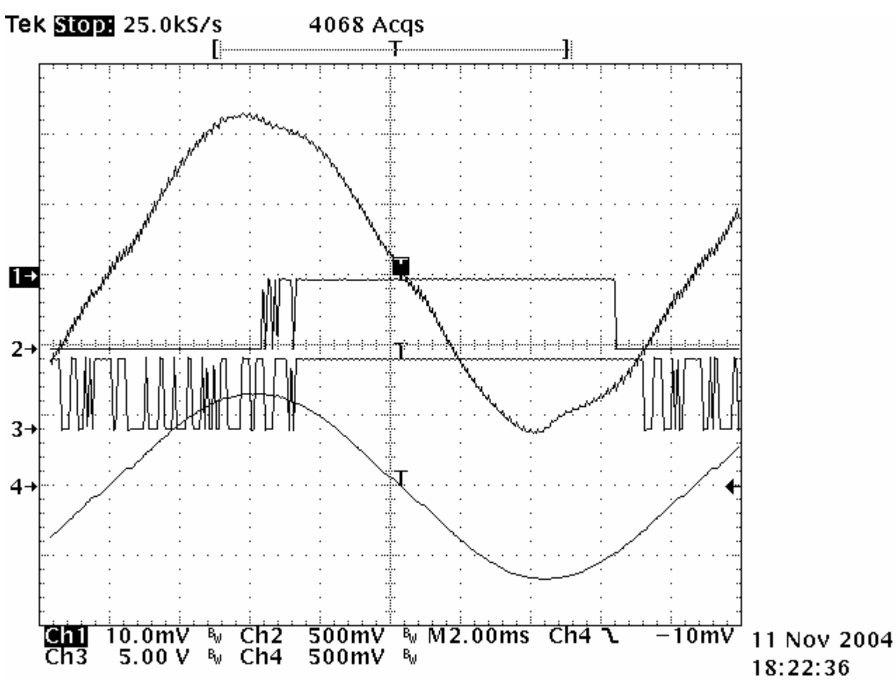


Figure 55 AC Test waveforms

ITP Conclusions

In this part of the report are outlined the major IPT design parameters and material selections. The alternative topologies and transformer designs are also discussed. We explain in detail how to integrate the transformer and inductance functions and show the approaches to prevent magnetic saturation.

Experimentally, the effort demonstrated that a 7.1 kg, free air-cooled, three-phase interphase transformer is capable of filtering up to 260 kVA (with foil construction). This corresponds to 27.3 g per kVA. The total power loss for the unit at rated power is about 67 W. As such, the energy efficiency of the filter in a DC application is less than 0.06% when the duty cycle is 50%. Under sinewave AC conditions, the VA rating of the unit is 92 kVA – which corresponds to 77 g per kVA.

It was also demonstrated that by selecting appropriate core aspect ratios, adequate leakage inductance can be provided such that external inductance is not required. Thus, a single magnetic element can provide both the required transformer and inductance functions.

The IPT concept experimentally demonstrated and exceeded the design predictions. The phase interphase transformer fabricated with cooper foil construction (7.1 kg), was capable of filtering up to 260kVA of power (72 kg air cooled inductor). This shows more than an order of magnitude weight reduction.

6. Commercialization/Business Plan

This section describes AeroVironment Inc.'s (AV) commercialization plan for the high power density inverter with IPT technology. During this program the existing inverter technology was upgraded and the IPT concept successfully demonstrated, an important step in taking the technology forward. AeroVironment has extensive experience related to electric and hybrid electric vehicle development along with the related power conversions and energy storage systems (e.g., fuel cells, power electronics, advanced batteries, fast charging systems, battery management systems, etc.). As a result, we have developed intimate and lasting relationships with many of the major automotive companies such as General Motors, Ford, Chrysler, Toyota, and such Tier I suppliers as Delphi and Delco Remy International. We have also worked very closely with the Army, Air Force, Navy and DARPA to develop and commercialize military-ready, electric and alternative energy products.

AV has successfully taken a number of concepts from initial idea through commercialization with product sales currently totaling several million dollars per year. One of these is a recent Air Force Phase II SBIR project to develop Multiple Vehicle Charging Stations for electric vehicles.

The following questions address the top-level commercialization effort.

First Planned Product – The initial product would be a lightweight; high power density liquid cooled power stage and significantly reduced magnetic volume compared to existing power stages. This version of the product would be targeted for automotive and distributed generations applications and would liberate significant space and weight that could be then used for other, mission critical applications. The product would also improve the power quality due to Digital Signal Controls, optimizing the operation and performance of sensitive onboard electronic systems and devices. Significant performance and reliability testing will ensure that the product meets strict automotive and military "-ability" standards.

Probable Customers and Market Size – Initial customers for this lightweight power stages will likely be vehicles and distributed generation system developers, for the Army's FCS and shelter program whom the benefits of volume and weight reduction will deliver the most value. Initially this market could represent $1 - $3 million/year in 2007 to 2008, but based on adoption of this technology across other applications, it could grow to a $35 - $50 million/year opportunity within the subsequent 5 years. The experience and volume afforded by the this applications will enable ongoing cost reduction and performance improvement, resulting in a more compelling value proposition for the commercial market.

In the commercial arena this product would deliver unique value to hybrid electric vehicles, whose penetration continues to grow rapidly through a combination of innovative packaging such as Toyota's Prius, Honda's Insight, Ford's Hybrid Escape SUV, and General Motors' "mild" hybrid Silverado pickup truck, and increasing fuel prices. Projections for commercial hybrid vehicle sales range from 535,000 to 3.5 million units per year in 2010, up from an estimated 100,000 sold in 2004.

The final product goal is to develop high-density universal power stage that could be used in different power processing applications like DC-DC and DC–AC or AC-DC (PFC) with single DSP controller. The markets and potential customers are listed below:

- Vehicle Market:
    - Commercial – Hybrid and EV vehicles – Chrysler, GM, Honda, Toyota,
    - Military – Future Combat Vehicles – BAE 5000 units,
- Distributed Generation:
    - Variable speed generators: Military: Fermont, Marvin, Onan.
    - Variable speed generators: Commercial: Magnum, Light Engineering,
- Renewable:
    - Photovoltaic – Power Light, Shell, APS
    - Wind Power –
    - Ocean Power
- Avionics – Ground power unit – 60-400Hz converters – 20M market potential
- Marine - DC-AC 60Hz and 400Hz Converters (Espey) - 10M market
- Power quality market – APC
- Fuel Cell – Idatech

Companies such as the major automobile manufacturers represent potential customers that would likely best be accesses through the “tier 1” supplier cadre (i.e., Delphi, Visteon, etc.).

Major global inverter suppliers such as Xantrex, Siemens could also benefit from incorporating the high-density topology into their designs.

The renewable energy market exhibits attractive characteristics. Worldwide, alternative energy installed capacity exceeded 39,000 MW in 2004, having grown 500% since 1997. An estimated 6,400 MW of wind was in place in the United States at the end of 2004. The solar energy production in the United States is estimated at 300 MW. As US state legislatures and utilities mandate and begin to implement renewable portfolio standards, wind and solar energy is positioned to receive the greatest benefit due to its relative cost advantage, perceived reliability and predictability, thereby driving demand for components such as inverters and magnetics.

In addition to the vehicle market, the power quality and backup power industry (“UPS”, or uninterruptible power supply) offers incremental market opportunity for the product based in part on the current limitations of lead acid batteries, including their inability to respond adequately to very rapid fluctuations in power supply and quality.

<u>Money Required to Bring This Technology to Market</u> – AeroVironment typically requires $2 - $5 million to bring a product to market, depending on technical complexity, manufacturability, and the scale of the sales & distribution effort. The high-density inverter has many potential applications, which means the sales & distribution effort is considerable, and requires reps and distributors. Thus we estimate $5 million will be required to optimize the inverter for different applications, test, and market initial versions of the unit. Of this funding requirement, the DOE funds of $450,000 allowed for the completion of the demonstration phase. This was an important step in demonstrating to potential end users that the technology delivers meaningful value to their systems. Potential sources of additional funding could include internal AV funds, DOD, DOT and OEMs such as General Electric, BAE, Lockheed and others.

Marketing Expertise – AV benefits from over 30 years of experience selling products and services to end users, channel partners and OEMs. Our dedicated marketing resources, with deep experience in technology and products businesses, helped to launch our PosiCharge business into the market-leading position it enjoys today. AV is also very familiar with supplying the US government through its industry-leading small UAV business. Several AV marketing professionals now focus on new technology introduction, and would be dedicated to the Lightweight Power Inverter. Additionally, current AV initiatives in the renewable energy arena represent potential synergy for inverter sales efforts in the wind energy industry.

7. Final Conclusion and Summary

AeroVironment's advanced inverter packaging technology, based on discrete components, has been in development for years. This patented thermal management concept offers the highest know power-to-size ratio for its class.

The three main objectives of this DOE program were to:

- Optimize and verify AV's existing packaging concept (Inverter Development)
- Validate the performance in a real application (Grid Tied Test Fixture)
- Analyze and validate the new Interphase Transformer concept to reduce magnetics

Thanks to this DOE program, the following upgrades were made to AeroVironment's Inverter Technology:

Size and weight improvements – power dissipation of each power semiconductor was increased by about 12%, which means that the power density of inverter units was increased by approximately 10%.

Reliability improvement. Elimination of the thermal pad, enhanced thermal cycling and lower thermal impedance of the IXYS semiconductor improved the inverter reliability. The newly developed gate drive circuit has the ability to reliable operate at wider temp range (–40C +100C), and higher switching frequency 100kHz.

Cost improvement. The latest analysis shows that the cost reduction of the improved inverter, over conventional design approaches using conventional IGBT modules, was increased by an additional 10% due to direct component saving and the simplified assembly and verification process.

The new design is fully applicable for automotive and distributed generation inverters:

- The power stage and gate drives are capable to operating at temp up to 90C
- The inverter reliably operates with fluid coolant temp up to 90C
- The max output power level is 50kW (at 90C coolant) or 90kW (at 65C coolant)
- Inverter Voltage Bus: 400VDC
- Proved the operation at harsh automotive environment with excessive vibration and shock
- The neutral phase was added to the inverter for dist. generation applications
- The power stage interfaces with a digital controller

The "Advanced Modular Inverter Technology" was validated during the performance, durability, environmental testing.

The "Grid Tied Load Bank" text fixture was developed based on Delphi requirements and included two high- density Alpha inverters. The fixture was designed to test motor drives with PWM output up to 50KVA and was capable to simulate typical linear RLC loads. The performance and acceptance tests were concluded at AV's facility.

The “Interphase Transformer Technology” introduces a new era in power conversion with a scalable, modular, and flexible design architecture. The IPT technology concept that replaces each semiconductor phase with three sub-phases and reduces the inverter magnetics by 36%, was successfully analyzed, demonstrated, and validated.

This final report outlines the major design parameters and material selections as well as discusses the alternative topologies and transformer designs. It explains in detail how to integrate the transformer and inductance functions and shows the approaches to prevent magnetic saturation.

The IPT concept was experimentally demonstrated and exceeded the design assumptions. The phase interphase transformer fabricated with cooper foil construction (7.1 kg) was capable of filtering up to 260kVA of power (72 kg air cooled inductor). This shows more than an order of magnitude weight reduction.

The “Advanced Modular Inverter with Interphase Transformer Technology” has great commercialization potential. This initial product would be targeted for automotive and distributed generations applications and would liberate significant space and weight that could be then used for other, mission critical applications.

Initial customers will likely be vehicles developers, for the Army’s FCS program with initial market $1 - $3 million/year in 2007 to 2008, but based on adoption of this technology across other applications, it could grow to a $35 - $50 million.

Projections for commercial hybrid vehicle sales range from 535,000 to 3.5 million units per year in 2010, up from an estimated 100,000 sold in 2004.

In addition to the vehicle market, such other markers as distributed generation, power quality, renewable, and the backup power industry offer significant market opportunity for this technology.

Appendix A – Environmental Tests: Operating Temperature Test
Appendix B – Environmental Tests: Thermal Cycling Test
Appendix C – Environmental Tests: Vibration Test
Appendix D – Environmental Tests: Shock Tests